# Università Degli Studi Di Napoli "Federico II"

## Dipartimento di Ingegneria Elettrica e Tecnologia dell'informazione (DIETI)



### PhD Thesis in

### Electromagnetic Compatibility Measurement

## Experimental Study about the Immunity Features of Field Programmable Analog Arrays (FPAA)-based Biomedical Application Devices to Radiated Disturbance

BY

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*... To*

*My Parents...*

# ABSTRACT

This research activity is based on the assessment of the immunity features of a field programmable analog array (FPAA) circuit to radiated disturbance. The methodology is focused on the evaluation of the effects of the radiated electromagnetic field onto the functional and operational characteristics of a front-end element to be used in ECG signal conditioning devices. More specifically, possible effects of electromagnetic disturbance on the parameters of the ECG signal, within a range of frequency from 250 MHz to 3 GHz, are investigated.

The research is carried out with a methodology based on both time and frequency domain analysis, relying on a typical ECG signal. The obtained measurements revealed a complex effect of the EM radiation on the FPAA input and output channels, which consist not only of additive noise on the useful signal, but is also causing an important offset shift, a superposition of several harmonics of the amplitude-modulation carrier added to the useful signal on both channels, and a non linear behavior of the FPAA. Moreover, the electromagnetic disturbance has a considerable effect on the time duration of different parts of the ECG signal (P-wave duration, PR interval to name a few) which can lead to wrong diagnosis. The main objective of this work is to contribute and propose modifications to the immunity test standards for these kind of applications.

# Acknowledgments

First and foremost, I would like to deeply thank my thesis supervisor, *Prof. Nicola Pasquino*, for directing this research, for his advices and encouragement, and especially for his patience and trust all along this thesis. Thanks also to him for providing an excellent working environment and maintaining a great atmosphere in the laboratory. Also would like to thank *Ing. Massimo Attanasio* for his assistance all along my work in the Electromagnetic compatibility laboratory.

A special thank goes to *Ing. Grillo Domenicantonio* for his help and assistance to establish the necessary programming for this work. Also would like to thank *Dr. Rosario Schiano lo Moriello* and *Ing . Attilio Marrese* for their precious help.

A great thank to all the wonderful people I met in the Measurement laboratory: *Annalisa Liccardo, Giuoliana Di Florio, Mauro D'Arco, Giacomo Ianniello, Alessandro Teotino* and *Francisco Bonavolontà,* for the great working atmosphere and the lovely time we spend together. Thank you very much and sorry if I forget some one's name.

I will never thank enough *Mr. Guido Celentano* from the physical department for All …… Grazie Mille Guido.

I will never thank enough my *mother* and *father* to whom I dedicate this dissertation and to all my family with special acknowledgment to my little angel *Akram*, my sisters *Nadjet* end *Basma*, my brothers *Imad, Nadjib* and *Hicham*.

I will never thank enough my husband *Nassim* for his comprehension, patience, help and support. And above all I thank God for giving me the will and means to achieve what I have achieved so far.

# SUMMARY

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# GENERAL INTRODUCTION

# INTRODUCTION

Electromagnetic compatibility (EMC) describes the ability of any electrical or electronic system, machine, appliance etc. to operate without malfunction in a disturbing electromagnetic environment while not itself disturbing the operation of other components of the system or of other systems in the same environment [1]. As a discipline EMC, represents nowadays an important field of research & development area related to a large variety of scientific areas, from the printed circuit board, communication systems and immunity tester to very critical applications in nanotechnology, photonic and metamaterials. Thus, it is not surprising that the cost of EMC/EMI analysis at the design level is up to 7 % of the total product cost, and the subsequent incorporation of EMC measurement for a finite product can increase its cost of 50% [2]. These rates reflect the reality that EMC/EMI analysis is a crucial part of the manufacturing industry for automotive, mobile phone, and portable and implantable biomedical apparatus, in which EMC analysis should give accurate, reliable and precise results.

On the other side, nowadays, homecare apparatuses are more and more requested with the increase in the use of this mode "homecare" in healthcare services, because of its low cost fees and the comfort it can give to the person. Those apparatuses are most of the time portable or implantable electronic systems, which are used for diagnosis of health problems or organ's malfunctions, for controlling the functionality of vital organs, and also for monitoring to contribute into the rehabilitation of disabilities and organ's malfunctions. The design of those electronic systems is based on a typical architecture which is common whether the application is portable or implantable, with taking in account the appropriate dimensions, the performances related to the nature of the application and the response expected from the system. This architecture simply consists of signal conditioning block, signal processing block, analog-to-digital/ digital-to-analog conversion blocks, a display block, and other complementary blocks. Those apparatuses are low power consumption systems, so they are home line power supply or battery powered systems. They are highly sophisticated and small sizes, due to the use of high level of system integration technology, in which the most used circuits are the ASICs (Application-

Specific Integrated Circuit). Actually ASICs are high cost fabrication fee circuits, because of the high cost the ASICs technology requires and the considerable design and prototyping time the applications need. However, today, in the area of sophisticated and low cost commercialized circuits, we can find very interesting opportunities between programmable analog circuits (FPAAs) and programmable digital circuits (FPGAs) which offer a very good flexibility and fast prototyping solutions to the designer. In the present, even with the existence of very sophisticated apparatus like pacemakers, the use of those programmable circuits is making the work on biomedical applications an actuality, where the trend is to replace the ASIC circuit by the association of FPAA for the analog part and the FPGA for the digital one, to make these devices and apparatus less expensive. However, this interest is focusing more on the analog part of the biomedical applications devices where the use of FPAAs can be very beneficial.

Actually, in the literature of the last 13 years, the biomedical applications involving FPAA are lot and variable, touching a large variety of signals as electroencephalography (EEG) (for record and processing system [3] or neuro-stimulator system [4]), electromyography (EMG) [5] and in particular electrocardiography (ECG) signal since it is the most world wide used record in diagnosis and monitoring operations. For instance in [5] was reported the implementation of a general front end amplifier for EMG and ECG signals, suitable for telemedicine systems and wearable devices, where the dynamic re-programmability of the FPAA was explored to change the amplifier's parameters to ensure the requirements of each signal to be amplified. Also, [6] has reported the implementation of an intelligent signal acquisition system using both FPAA as an adaptive front end part and FPGA circuit as FPAA programming monitor and digital processing signal part, this implementation target portable systems and can be adapted to any kind of bioelectric signal. And [7] has reported the use of a configured FPAA as QRS detector to detect the heart rate using ECG signal, this application can be used in cardiac assist devices or artificial stimulator and pacemakers. Recently, it has been reported in [8] the design of biomedical field programmable analogue array using the AMS 0.35 μm technology for

low frequency and low power consumption to improve FPAA performances in biomedical application (which are very low frequencies applications).

However, The home environment (or even in hospitals, or outside) where those biomedical systems should operate, is crowded of other electronic systems, and each one of them is supposed to be able to work properly in the presence of the others which are emitting electromagnetic energy, thing which is not easy at all to control with the rising number of commercialized electronic applications, and which are somehow important in our daily life. In this context, studying the susceptibility of such systems to the external disturbances is extremely important and recommended to determine how much the system is immune against external turbulence from RF transmission and electromagnetic phenomenon (from natural sources or human made sources). A particular care is to be given in this field to these biomedical applications, taking into account the fact that most of them are portable or implantable devices usually used for life supporting purposes, which mean, that a minimum disorder to this devices function, caused by any kind of disturbance, can lead to false diagnosis and can cause a disaster (death of the patient in the worst cases). Yet, this kind of immunity test of such biomedical applications involving FPAAs circuits is not well covered in the actual scientific research and publications.

In this study our aim is to evaluate the immunity of an FPAA circuit (AN221E04 from Anadigm) configured as a biomedical signal conditioning element concerned by the ECG signal to be used in diagnosis and monitoring systems, to Electromagnetic (EM) radiated disturbance . Here, this evaluation is concerned by two aspects; the first one is about the assessment of the FPAA circuit functionality under the effect of EM disturbance based on IEC EN 61000 4-3, IEC EN 61000 4-20, ANSI/AAMI EC-11, ANSI/AAMI EC-38, ANSI/AAMI 60601-1-2:2007 and ANSI/AAMI PC69:2007 standards as an electronic and medical device. While, the second one is to study the possible effect of this disturbance on the morphologic and temporal parameters of different elements on the ECG record, by focusing on the time duration parameter of different parts on the ECG record mainly: the P wave, the QRS complex, the PR interval and the QT interval. This experimental study is based actually on two different

methodologies employed to evaluate the EM effect. The first one is based on a differential approach using a direct measurement, while the second one is relies on typical ECG signal characteristics and its frequency domain analysis.

## BIBLIOGRAPHY

[1] D.L. Sengupta (The University of Michigan and The University of Detroit Mercy), V.V. Liepa (The University of Michigan) "*APPLIED ELECTROMAGNETICS AND ELECTROMAGNETIC C 0 M PATI B I L ITY*", A JOHN WILEY & SONS, INC., PUBLICATION, COPYRIGHT 2006, ISBN-I 3 978-0-471-16549-1.

[2] Nikolaos V. Kantartzis, Theodoros D. Tsiboukis "*MODERN EMC ANALYSIS TECHNIQUES. VOLUME II: MODELS AND APPLICATIONS*", A PUBLICATION IN THE MORGAN & CLAYPOOL PUBLISHERS SERIES, COPYRIGHT 2008, DOI: 10.2200/S00114ED1V01Y200804CEM022, ISBN: 9781598293203.

[3] Zbrzeski, A, Hasler, P. ; Kölbl, F. ; Syed, E. ; Lewis, N. ; Renaud, S. "*A programmable bioamplifier on FPAA for in vivo neural recording* », Biomedical Circuits and Systems Conference (BioCAS), 2010 IEEE, 3-5 Nov. 2010, DOI: 10.1109/BIOCAS.2010.5709584.

[4] Jingai Zhou; Se Joon Woo ; Se Ik Park ; Seung Woo Lee ; Hum Chung ; Sung June Kim; "A Neurostimulator Design for Long-term Animal Experiments"; Frontiers in the Convergence of Bioscience and Information Technologies, 2007. FBIT; 11-13 Oct. 2007; pp: 453 – 457; DOI: 10.1109/FBIT.2007.67.

[5] U Fai Chan et al; "Flexible implementation of front end bioelectric signal amplifier using FPAA for telemedicine system"; Proceeding of the 29th annual international conference of the IEEE EMBS, Lyon France; August 23-26 2007; pp: 3721-3724.

[6] P Antonio Mou et al; "Portable Intellegnet Bioelectric signals acquisition system with an Adaptive front end implemented using FPGA and FPAA"; IFMBE Proceeding, vol 25; WC 2009; pp:348-351.

[7] Malcher, Andrzej; Pietraszek, Stanislaw; Przybyla, Tomasz "*Hybrid QRS detection circuit based on dynamic reconfigurable field programmable analog array*"; 10th IFAC Workshop on Programmable Devices and Embedded Systems 2010, Volume 10 | Part 1; pp: 48-53; DOI: 10.3182/20101006-2-PL-4019.00011.

[8] Comlekci, C. Baskaya, F. ; Dundar, G; "Field Programmable Analog Array Design for biomedical applications"; Signal Processing and Communications Applications (SIU), 2011 IEEE 19th Conference on; 20-22 April 2011; pp: 1056 – 1059; DOI: 10.1109/SIU.2011.5929836.

# CHAPTER I:

# ELECTROMAGNETIC COMPATIBILITY FUNDAMENTALS, ASPECTS AND STANDARDS

# I. INTRODUCTION

The widespread use of electronic circuits for communication, computation, control and automation, as well as in other purposes in our daily life makes it necessary for diverse circuits to operate in close proximity to each other at home, in office, in care, in hospitals, in airports .etc. All too often, these circuits affect each other adversely with the increasing of electromagnetic interference (EMI) problems, which are likely to become even more severe in the future; because of the use of large number of sophisticated electronic devices which are doted more and more of large scale integrated circuits to reduced the size of electronic equipment [1]. As circuitry has become smaller and more sophisticated, more circuits are being crowded into less space, which increases the probability of interference. And, their clock frequencies have increased dramatically over the years (in many cases to over a gigahertz).

Actually, testing for EMC compliant is today crucial more than ever in time and it will be primordial in the future with the new emerging technologies. In fact, taking in account EMC aspect and problems in earlier stages of electrical/electronic systems design reduces considerably the total cost of design, gives to the engineers higher flexibility in adapting EMC test techniques, and gives to the final device more chance to be a successful product in the market [1]. In reality, testing for EMC is usually effectuated at the prototyping phase, where the devices have all the characteristics of a final device, and where the access to change these characteristics is still possible.
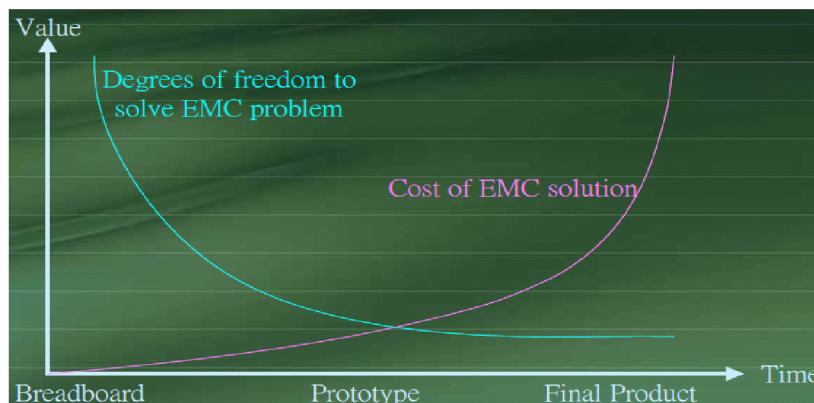


***Fig.I.1:*** *Time value and cost of EMC testing.*

According to [2], in the coming years the electromagnetic environment will drastically change with the high-speed digital lifestyle and the widespread proliferation of (wireless) devices which will, without well-timed and properly informed action, result in an increase of interference problems every where. Intentional electromagnetic threats are also now emerging to which unprotected systems will be vulnerable. Without a coordinated development program of regulation, this increasingly complex electromagnetic environment cannot be controlled anymore and will lead to more and more interference problems and safety hazards, possibly aggravated by intentional malicious aggressions.

This chapter is devoted to Electromagnetic Compatibility EMC, by giving some basic definitions, explaining EMC different aspects; outlining the different EMC related standards and regulations and summarising the standards we are using in this work. But, before going through these points, let's recall briefly some of the electrostatics, magnetostatics and electromagnetic principals.

## II. ELECTROSTATICS

Electrostatics theory consists of the description of all the physical phenomena related to the stationary electric charges interaction within a finite space. Where, at atomic level, the electric charges are the source of any electric field. Those electric charges can have either a negative charge associated to electrons ($q_e = -e$) or a positive charge associated to protons ($q_p = e$). However, both of them have the same magnitude of charge which equal to $e$ (1.6 x 10-19 Coulombs) [3].
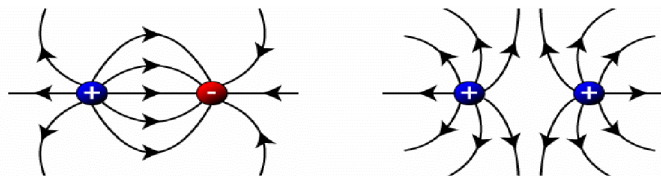


*Fig.I.2: Electrostatic force between charges.*

Any electric charge produces an electric field in the space that surrounds it, regardless of the existence of other charges anywhere in this space. Nevertheless, the existence of other charges in the neighbour is necessary to

senses the presence of the first charge and so define the electrical field. Here, the positive charge is considered as the source of an electrical field and the negative charge is considered as a sink of an electrical field. In an other word, the electrical field extends outward from the positive charge to terminates into the sink or the negative charge, inducing to the generation of an electrostatic force F between charges, this force can be repulsive for charges of same signs and attractive for charges of opposite signs (Coulumb's law) [4], and so, the intensity of the electrical field is defined as follow:

$$E = \frac{q}{4\pi\varepsilon R^2}\hat{r}$$

Where, $\hat{r}$ is a unit vector in the direction of the electric field, $q$ is the magnitude of the point charge, R is the distance from the observation point to the charge, and ε is the permittivity of the material in which travel the electrical field.

The disposition of charges in space can take a line aspect, surface aspect or a volume aspect; however, in all those charges distributions the principal of calculating the electrical field due to each charge is the same; by the application the superposition principal based on the summation of small portion of the line (*dl*), surface (*ds*), or volume (*dv*), over the entire line, surface, or volume.

Any charges distribution arise a potential energy that we define as the electrical potential V or voltage, which is a scalar value expressed in Volt, for instance, a specific volume charges distribution arise an electric potential given by:

$$V = \int_v \frac{\rho_v\,dv}{4\pi\varepsilon R} \quad (V)$$

Where, $\rho_s$ is the density of charges in the surface, and $\varepsilon$ is the media permittivity.

Along with the electric field intensity, there is an associated electric flux density. Like the electric field intensity, the electric flux is also a vector. The electric flux density is commonly referred to as the electric

displacement field; the two quantities are identical and can be interchanged. The flux density is proportional to the electric field intensity, and they are related via the permittivity of the material.

When discussing EMI/EMC There are two fields which in reality that we must look at the electric field and the magnetic field. From the equations presented so far in here, it can be seen how different charge distributions can produce an electric field, and a volume charge can result in a voltage potential. The electric field is the dual to the magnetic field. The magnetic field is produced by current distributions and has some similarities to the electric field. Both the electric and magnetic fields couple to create EMI issues, and both must be understood. Where the electric field is capable of inducing a voltage in a wire, a magnetic field is capable of inducing a current.

## III. MAGNETOSTATIC

In Magnetostatics domain we deal with static electric currents (electric charges moving with constant speeds), and the interaction between these currents. In a magnet, the magnetic field has a particular property that unlike the electric field lines, which leave a positive charge and end up at a negative charge, the magnetic field lines are usually closed on themselves, without heads or tails [4]. Mathematically, this can be stated by a vanishing divergence of the magnetic field.

$$\nabla \cdot B = 0$$

Where, the density of the magnetic field (**B**) is related to the magnetic field intensity (**H**) through the permeability (μ) (describing how well a magnetic field is able to travel through the material) of the material the fields are in.

$$B = \mu H$$

Like electric charges, currents can also have multiple distributions. These distributions are commonly in the form of a line current (**I**), surface current (**K**), or volume current (**J**). And the magnetic field intensity can be solved for each distribution from:

$$H = \int_v \frac{Jdv}{4\pi R^2} \hat{r}$$

A simple way to visualize the cross product of two vectors, and determine the direction of a magnetic field, is to use the famous right hand rule. By pointing the thumb on your right hand in the direction of conventional current, and wrapping your fingers around the wire, the direction of the magnetic field is in the same direction as your fingers. In the SI unit for the magnetic field, sometimes called the magnetic flux density or magnetic induction, is Tesla (T). Here, the magnetic field has an associated potential vector A, which for a specific volume can be defined as:

$$A = \int_v \frac{\mu J dv}{4\pi R}$$

## IV. ELECTROMAGNETICS

the laws of electrostatics and magnetostatics can be summarised in two different sets of time-independent, uncoupled partial differential equations, called also, the classical electrostatics and the classical magnetostatics equations, they reveal that there is nothing a priori that connects E directly with B, so, we consider classical electrostatics and classical magnetostatics as two separate and mutually independent physical theories. However, when we include time-dependence, the fields are no longer static and vary with time, the fields couple to each other. While, a time-varying electric field will generate a magnetic field, a time-varying magnetic field will generate an electric field. Using laws determined by Gauss, Faraday, and Ampere, Maxwell came up with a set of four differential equations which describe electromagnetic fields [4].

- ✓ Gauss's law states that *"The electric flux through any closed surface is proportional to the enclosed electric charge."*

- ✓ Faradays law states *"The induced EMF in any closed circuit is equal to the time rate of change of the magnetic flux through the circuit."* commonly used in generators and transformers.

✓ Lenz also contributed to Faraday's law by stating *"The current in the circuit is always in such a direction as to oppose the change of magnetic flux that produced it."*

✓ In addition Amperes law is used to relate the magnetic field around a closed loop, to the magnitude of the current passing through that loop

✓ Maxwell has modified all the previous laws to compensate the displacement current and expressed them mathematically in order to summarize the description of the  electromagnetic phenomena into four famous equations (Differential form of Maxwell's equations):

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0} \qquad \text{(Gauss's electric law)}$$

$$\nabla \cdot B = 0 \qquad \text{(Gauss' law for magnetic fields)}$$

$$\nabla \times E + \frac{\partial B}{\partial t} = 0 \quad \text{(Faraday's law)}$$

$$\nabla \times B - \frac{1}{C^2}\frac{\partial E}{\partial t} = \mu_0 J \quad \text{(Ampere-Maxwell law)}$$

$B$ = Magnetic field ($T$ or $Wb\ m^{-2}$)

$E$ = Electric field (coulombs/square meter; $C\ m^{-2}$)

$\rho$ = Electric charge density (coulombs/cubic meter; $C\ m^{-3}$)

$J$ = Electric current density (amperes/square meter; $A\ m^{-2}$).

Commonly when discussing EMI, simple shapes such as a straight wires or loops have an antenna effect which radiates or couples interference to systems in its neighbour, and using Maxwell equations is crucial to solve the E and B fields for these shapes. Here again, the expressions for the both fields vary depending if we are in the near or the far field, where the requirements to be considered are the distance to the observation point (D) and the wavelength of the signal (λ):

$$D < \frac{\lambda}{2\pi} \quad \text{Near field requirement.}$$

$$D > \frac{\lambda}{2\pi}$$ Far field requirement.

For the far field both E and B fall off as 1/D, however, in the near field E and B will fall off as $1/D^2$ or $1/D^3$ depending on if the source is a straight wire or a loop [5]. This shows how the fields behave differently, and should help to predict the amount of radiated emissions due to the antenna effect of wires or printed traces.

## V. ELECTROMAGNETIC RADIATION

Electromagnetic waves are created by the vibration of an electric charge. This vibration creates a wave which has both an electric and a magnetic component. This wave transports its energy through a vacuum at the speed of light (3.00 x $10^8$ m/s) and at speeds less then that in different medium [4].

Electromagnetic waves are what constitute electromagnetic radiation which is actually based on a particle model, and are the fundamental source of EMI problems. At atomic level the specific energy of an EM wave is quantized, meaning it consists of discrete packets of energy transported by photons, which are absorbed and emitted due to changing energy levels of electrons, and will have an energy level defined by the Plank-Einstein equation ( $Energy = hf$ , $h$=6.626*$10^{-23}$ j.s is Plank's constant and $f$ is the photon frequency).
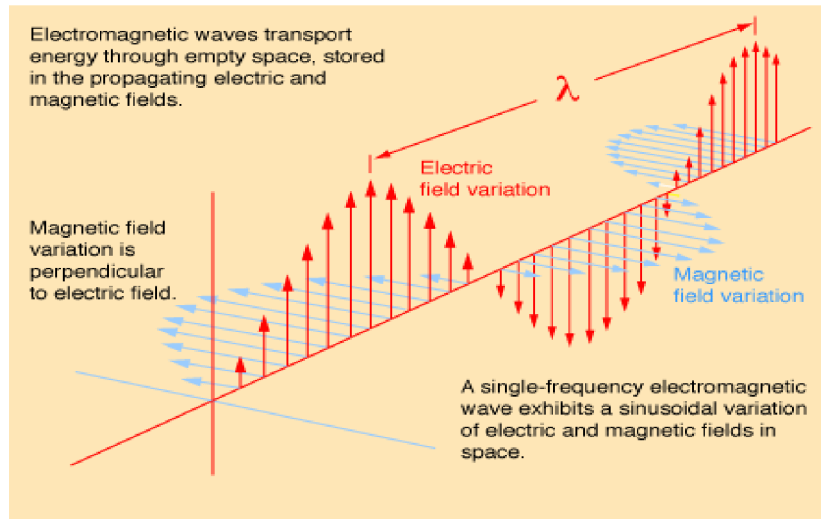


*Fig.I.3:* *Electromagnetic wave propagation.*

Depending on the kind of atom and the amount of energy, this electromagnetic radiation can take the form of heat, light, ultraviolet, or other electromagnetic waves according to their wavelength extending from radio frequency to Gamma rays frequency.

Based on Plank-Einstein equation, Maxwell predicted that EM waves were governed by the same fundamental laws that light obeys. This was later confirmed by Hertz in 1887 that proved the photoelectric effect in electrons at the molecular level [6].
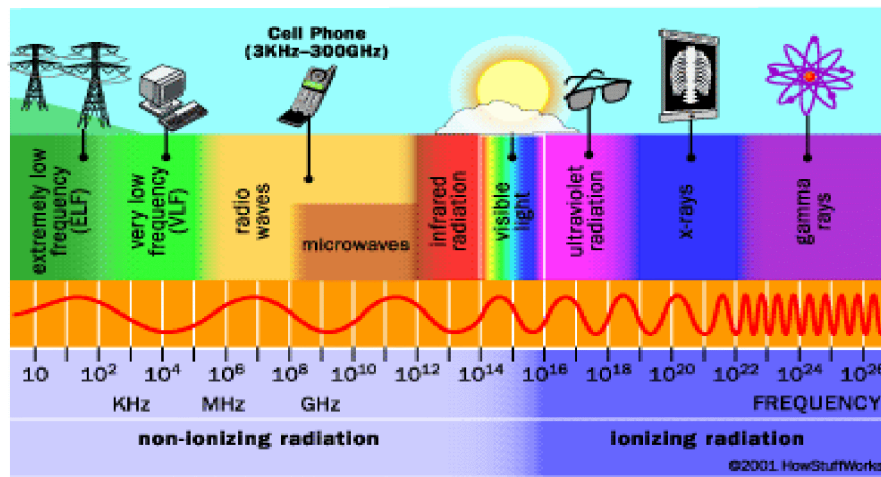


***Fig.I.4:*** *Electromagnetic wave spectrum [7].*

For an EM wave, electric and magnetic fields are proportional to each other, and the ratio between them depends on the material or the medium in which the wave travel. In addition, the electromagnetic wave has characteristics associated with it such as the velocity of propagation ($v_p$), angular frequency ($\omega$), attenuation factor ($\alpha$), and phase constant ($\beta$). These characteristics impact all the wave as it travels in time. For instance, the free space is lossless with an intrinsic impedance equal to 377 $\Omega$, and no attenuation therefore, $\alpha = 0$, the angular frequency ($\omega$) and phase constant ($\beta$) are defined by $\omega = 2\pi f$, and $\beta = \omega/c$ (c is the speed of light in the vacuum). Thus, the velocity of propagation of a wave in free space is actually equal to the speed of light.

The skin depth of a material is an other parameter worthy to take in account when dealing with EMI; it determines how deep an EM wave is able to

penetrate the medium. The depth the EM wave is able to penetrate is a function of the frequency of the wave incident, and the conductivity of the material. This parameter is important because it will have an impact on the evaluation of the working reliability of the material in presence of electromagnetic disturbance and to determine the type of shielding that must be used [6].

## V. 1. SOURCES OF ELECTROMAGNETIC RADIATION

Electromagnetic fields exist everywhere all over our surrounding environment including our home, school and work place. Electromagnetic fields are generated either by natural or human-made sources

### V. 1. 1. NATURAL ELECTROMAGNETIC RADIATION

In our natural environment, we are constantly surrounded by natural sources of electromagnetic radiation, which can act as sources of electronic interference. The primary source of natural electromagnetic radiation, however, comes from the sun. [8] The earth is constantly bombarded by all types of electromagnetic energy from the sun, and energy that is not filtered out by the atmosphere has the potential of causing interference. As the case of lightning, which, In addition to disabling information systems through power outages, it can also produce enough interference to temporarily disrupt communications [9]. Under normal circumstances, the energy from the sun is not great enough to interfere with electronic equipment. However, solar flares (the release of magnetic energy on the sun's surface [10]) can send enough electromagnetic energy to the earth to disrupt all types of electronic devices on the sun-facing side of the earth.

### V. 1. 2. MAN-MADE ELECTROMAGNETIC RADIATION

In addition to natural sources, electromagnetic interference can also arise from regular use of electronic devices which are considered as man-made electromagnetic radiation source. Like television, hair, and any wire that carries electronic signals (e.g. speaker wire, monitor cables, internal wiring, etc.) can transmit interference if its protective covering is damaged. [11] Some electronic devices, such as fluorescent lights and laptop computers, emanate a small electromagnetic field during regular use that may interfere with nearby electronic equipment. Finally, signals from wireless devices

such as mobile radios, radar systems, wi-fi modems and cellular phones are considered also as an important source of electromagnetic radiation.

## V. 2. Classification of electromagnetic radiated energy

According to the amount of energy they carry, the radiated electromagnetic waves are classified as ionizing and non-ionizing [12].

### V. 2. 1. Non-ionising radiation

Electromagnetic fields which cannot break down molecular bonds are called non-ionising radiation. Many artificial sources of electromagnetic fields, surrounding us daily (including radio signals); are non-ionising. Thus because, the quantity of energy they carry cannot break down chemical bonds within cells and tissues.

### V. 2. 2. Ionising Radiation

Some electromagnetic waves carry such large quantities of energy that they can ionise particles of matter and consequently break down the chemical bonds between molecules. X-rays used for both diagnostic and therapeutic purposes (radiotherapy), gamma-rays (emitted by radioactive materials) and cosmic radiation, all have this ability and are classified as ionising radiation.

# VI. ELECTROMAGNETIC COMPATIBILITY (EMC)

## VI. 1. Definitions

### VI. 1.1. Electromagnetic Interference (EMI)

Electromagnetic Interference (EMI) is defined as a: "Degradation of the performance of an electrical/electronic equipment, transmission channel or system caused by an electromagnetic disturbance." [13] EMI is thus; most often, an unintentional energy that effects can range from a simple degradation of the signal to a total loss of it (EMI can also be a desired property in radio jammers for example, where it is used to exploit the shortcomings of other equipment). However, EMI is a very wide concept which covers various types of different phenomenon. It can take form of both conducted and radiated emissions and thus can influence its surroundings in different manners.

## VI. 1. 2. ELECTROMAGNETIC COMPATIBILITY (EMC)

Electromagnetic compatibility EMC is defined as: "The ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment." A system is called electromagnetically compatible with its environment if it satisfies three criteria [14]:

✓ Is not susceptible to interference from other systems.

✓ Is not susceptible to interference from itself.

✓ And is not a source of interference to other systems.

## VI. 1. 3. ELECTROMAGNETIC SUSCEPTIBILITY

The electromagnetic susceptibility defines the inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance, in other word; it is the lack of immunity [15]

## VI. 1. 4. IMMUNITY

Immunity is a relative measure of a device or system's ability to withstand EMI exposure, while maintaining a predefined performance level of function. Based on the type of interference mechanism (radiated emission or conducted) the immunity can be:

✓ RADIATED IMMUNITY: which defines a product's relative ability to withstand electromagnetic energy that arrives via free-space propagation.

✓ CONDUCTED IMMUNITY: which defines a product's relative ability to withstand electromagnetic energy that penetrates it through external cables, power cords, and I/O interconnects [15].

## IV. 1. 5. THE COMPATIBILITY GAP

Because of the increasing of electromagnetic pollution in the environment, the susceptibility of electronic equipment to electromagnetic influences is increasing as well. Thus mean that the electromagnetic susceptibility of electronic equipment actually depends on two points [16]:
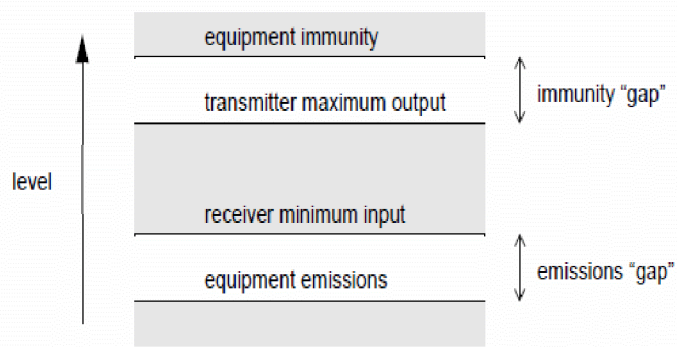
*Fig.I.5:* *The EMC gap.*

✓ The adoption of VLSI technology in the form of microprocessors, both to achieve new tasks and for tasks that were previously tackled by electromechanical or analogue means, and the accompanying reduction in the energy required of potentially disturbing factors.

✓ The increased penetration of radio communications, and the greater opportunities for interference to radio reception that result from the co-location of unintentional emitters and radio receivers.

In addition, more radio communications means more transmitters and an increase in the average RF field strengths to which equipment is exposed. These concepts can be graphically presented in the form of a narrowing electromagnetic compatibility gap, where the emissions level  and the immunity level gaps of the equipments do not have any intersection, so no mutual interaction between them (except in rare cases) [16]. However, the maintenance of some artificially-defined gap between equipment immunity and radio transmissions, and between equipment emission and radio reception, should be adjusted and updated regularly to ensure the electronic equipments immunity all over the time. This task is actually the purpose of the application of EMC standards.

## VI. 1. 6. Coupling (path, mode or mechanism)

The coupling is the mechanisms by which EMI is able to travel from a source of energy to a receiver. There are four basic coupling mechanisms: conductive, capacitive, magnetic (inductive), and radiative. Any coupling path can be broken down into one or more of these coupling mechanisms working together.
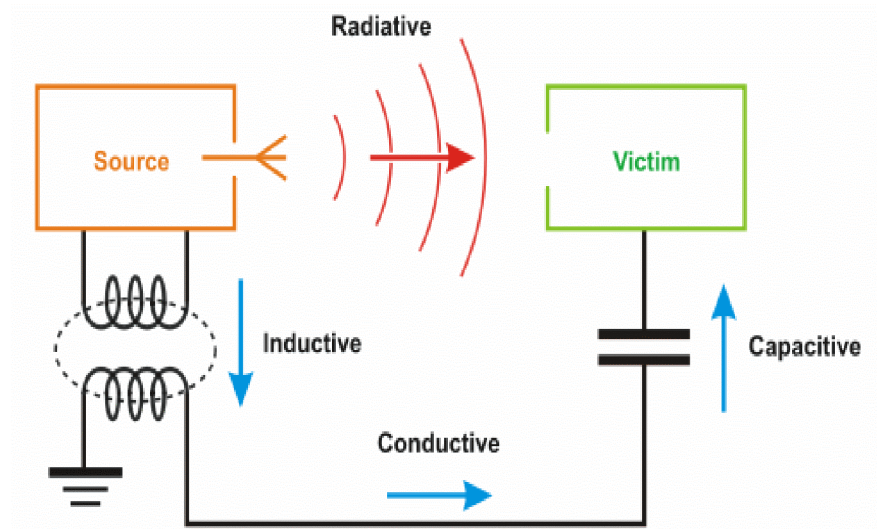
***Fig.I.6:*** *Different coupling mechanisms.*

## IV. 1. 6.1. Conductive coupling

Conductive coupling occurs when the coupling path between the source and the receptor is formed by direct contact with a conducting body, for example a transmission line, wire, cable, PCB trace or metal enclosure. Here, conducted noise is also characterized by the way it appears on different conductors, which can be either common mode noise or differential mode noise [17].

## VI. 1. 6. 2. Inductive coupling

Inductive coupling occurs where the source and receiver are separated by a short distance (typically less than a wavelength). Strictly, "Inductive coupling" can be of two kinds, electrical induction and magnetic induction. It is common to refer to electrical induction as capacitive coupling and to magnetic induction as inductive coupling [18].

  ✓ Capacitive coupling occurs when a varying electrical field exists between two adjacent conductors typically less than a wavelength apart, inducing a change in voltage across the gap.

  ✓ Magnetic coupling: Inductive coupling or magnetic coupling (MC) occurs when a varying magnetic field exists between two parallel conductors typically less than a wavelength apart, inducing a change in voltage along the receiving conductor.

## VI.1.6.3. Radiative coupling

Radiative coupling or electromagnetic coupling [19] occurs when source and receptor are separated by a large distance, typically more than a wavelength. Source and receptor act as radio antennas; where the source emits or radiates an electromagnetic wave which propagates across the open space in between and is picked up or received by the receptor.

## VII. Decibel expression (dB)

The decibel is nothing more than an expression of the ratio between two signals. The signals might be voltages, currents or power levels (at output and input of a system). When rendered in the form of decibel notation, however, the logarithms of the ratios are used to makes it possible to replace multiplication and division calculations with addition and subtraction [20].

There are three ways to calculate the decibel depending one whether a current, voltage or power level is intended. Most radio receiver work is based on the power decibel, so let's look at that one first. Recall that the decibel finds the ratio between two power levels, and expresses it as a logarithmic number. If P1 and P2 are the two signal levels, then the ratio is P1/P2. The equivalent Decibel value is:

$$dB = 10 LOG\left(\frac{P_1}{P_2}\right)$$  For Power ratio

$$dB = 10 LOG\left(\frac{V_1}{V_2}\right)$$  For Voltage ratio

$$dB = 10 LOG\left(\frac{I_1}{I_2}\right)$$  For Current ratio

Over the years different segments of the radio and electronics industry have created special decibel scales for their own use. All of them are based on the three equations given above. The differences are in the specified conditions under which the measurements are made, and the specific level used as a reference point. The standard reference voltage or power will be placed in the denominator of the equation, and is usually referred to as the "0 dB" reference level. This name comes from the fact that placing the same level

in the numerator produces a ratio of 1:1 or 0 dB. Several different special dB scales are listed below.

- ✓ **dBm**. These units refer to decibels relative to one milliwatt (1 mW) of power dissipated in a 50 Ohm resistive impedance (defined as the 0 dBm reference level), and is calculated from either 10 LOG ($P_{WATTS}/0.001$) or 10 LOG ($P_{MW}$). The dBm scale is used in describing receivers and amplifiers.

- ✓ **dBmV**. This unit is used in television receiver systems in which the system impedance is 75 Ohms, rather than the 50 Ohms normally used in other RF systems. It refers to the signal voltage, measured in decibels, with respect to a signal level of one millivolt (1 mV) across a 75 ohm resistance (0 dBmv). In many TV specs, 1 mV is the full quieting signal that produces no "snow" (i.e. noise) in the displayed picture.

- ✓ **dBmV**. This unit refers to a signal voltage, measured in decibels, relative to one microvolt (1 mV) developed across 50 Ohm resistive impedance (0 dBmV).

- ✓ **dB (Old).** An archaic dB unit used in the telephone industry prior to World War II used 6 milli-watts dissipated in a 500 ohm resistive load at the 0 dB reference level.

- ✓ **Volume Units (VU).** This unit is used in audio work, and largely replaces the old dB scale given above. In the VU scale 0 VU is 1 milli-watt dissipated in a 600 ohm resistive load.

## VIII. EMC ASPECTS

EMC is concerned with the generation, transmission, and reception of electromagnetic energy. These three aspects of the EMC problem form the basic framework of any EMC design. A source (an emitter) produces the emission, and a transfer or coupling path transfers the emitted energy to a receptor (receiver), where it is processed, resulting in either desired or undesired behaviour. And interference occurs if the received energy is enough to cause the receptor to behave in an undesired manner. The transfer of electromagnetic energy occurs frequently via unintended coupling modes.

*Fig.I.7: Basic constitution of the EMC problem.*

However, it is important to understand that a source or receptor may be classified as intended or unintended; depending on the coupling path as well as on the type of source or receptor and also on the effect of this interference on the emitter/receptor function. The identification of the EMC system components (emitter, coupling path and receptor) is not always trivial because of the structure of the system itself. In fact, the emitter and the receptor may be associated with two independent systems or both of them could be subsystems in a larger system. Indeed, the properties of the interference signals produced in the receptor are affected by the emitter characteristics (amplitude, spectrum, etc) and the properties of the coupling path. So, the problem may be further complicated by the fact that there may be multiple coupling paths in a given EMC problem. The prevention of the interference can be achieved by [14]:

✓ Suppressing the undesired emission.

✓ Reducing the efficiency of the coupling path.

✓ Reducing the susceptibility of the receptor.

Different systems can be susceptible to each others emission, so we speak here about an inter-systems EMC problem. However, some systems are susceptible to their own emission, and the EMC problem in this case is called intra-system.
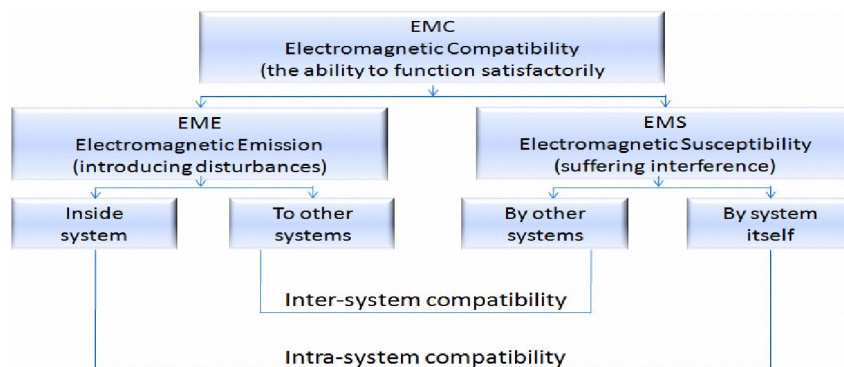


*Fig.I.8: Inter/intra system compatibility notion.*

Moreover, according to the nature of the coupling path, and depending on how the EMI is propagating, EMC problem can take four aspects [14]:

✓ Radiated emission.

✓ Radiated susceptibility.

✓ Conducted emission.

✓ Conducted susceptibility.
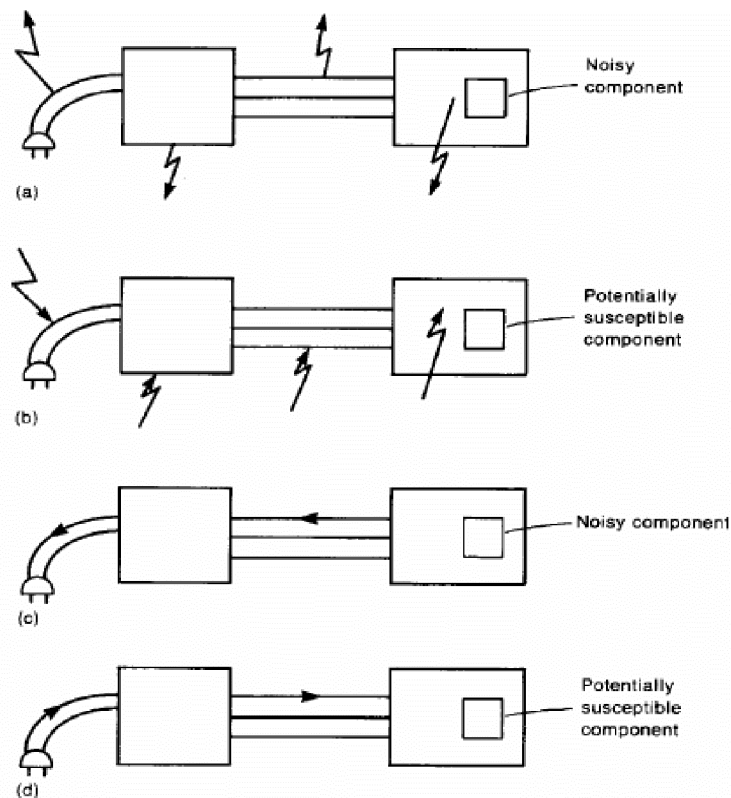


**Fig.I.9:** *The four basic EMC sub-problems: (a) radiated emissions; (b) radiated susceptibility; (c) conducted emissions; (d) conducted susceptibility [14].*

Where, the term "emission" is referred to the fact that an electric/electronic system can generate and emit an electromagnetic energy which can disturb other systems in its neighbour, and the term "susceptibility" is referred to the fact that an electric/electronic system has a high sensibility to pick up and be disturbed by the EM energy emitted by other systems in its neighbour causing its malfunction. However, the term "conducted" is referred to the conductive coupling path where a direct connection between systems is used (transmission line, cables, ac power cord, interconnections…etc), and the term "radiated" is referred to the radiative

coupling path which concern the propagation of electromagnetic energy along big distances between systems. Here, it is worthy to note that a conducted emission can produce a radiated emission in particular cases [14].

In order to reduce the effect of these EMC problems, electric/electronic systems and devices should satisfy a certain characteristic concerned by the tolerable level of interference called "Immunity level", in which those systems can function safely with the presence of other systems in their proximity and so it can be sold and used. This immunity level is actually achieved by a specific test called "immunity test" to fix for each specific system or device the required immunity level. According to the type of the EM interference (radiated or conducted) we should apply the appropriate immunity test:

## VIII. 1. RADIATED IMMUNITY

The purpose of these tests is to ensure that the electric/electronic device will operate properly when it is installed in the vicinity of high-power transmitters. The common types of such transmitters are AM and FM transmitters and airport surveillance radars. Manufacturers of such devices test their products to these types of emitters by illuminating the product with a typical waveform and signal level representing the worst-case exposure of the device and determining whether the device will perform satisfactorily [14].

## VIII. 2. CONDUCTED IMMUNITY

Conducted Immunity tests are performed to determine the ability of a device to withstand the presence of RF signals on the cables or power cords attached to the device. Here, low frequency signals (usually between 10 kHz to 80 MHz) are injected onto the data and power lines of a device. To simulate the coupling of low frequency signals onto the power and data lines, such as from a local AM radio station [21].

Nowadays, the electromagnetic interference environment is becoming increasingly cluttered as more small wireless devices are introduced into the market every day. In order to control and reduce the amount of interference effect on these devices, a set of EMC standards have been introduced. These standards represent in reality a kid of regulation and legislation to be used

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into the control of intentional and unintentional EMC, to prevent the interference.

# IX. EMC REGULATIONS AND STANDARDS

## IX. 1. STANDARD AND REGULATION

A standard is a published document which sets out specifications and procedures designed to ensure that a material, product, method or service is fit for its purpose and consistently performs the way is was meant to perform. However, regulation is the fact that; in order to market and export equipment to different parts of the world, manufacturers must be aware of the different EMC standards that exist.

## IX. 2. BRIEF EMC STANDARDS AND LEGALIZATION HISTORY

The new age of communication in Europe began 1892 when the German Parliament voted to create the "Law of Telegraph in the German Empire". This was the first law in the world that dealt with influences of electromagnetic disturbances on products and installations in the field of telegraph technique. This law also regulated the procedures to be followed in case such electromagnetic disturbances were found. People at that time had discovered very quickly that cables did disturb each other and the disturbances on telegraph and telephone communication were the most severe. Thus, The German Society of Electro-technicians was founded in 1893 [22].

However, more than 110 years ago EMC was not a big matter but this was changed immediately by the early part of the twentieth century, where few man-made sources of electromagnetic radiation were developed. And where the first crude radio receivers tended to be susceptible to interference from natural noise sources. The correction of this problem was usually a relatively simple task. Here, conflicts between early radio transmitters were easily resolved by changing frequencies or by simply moving the transmitter or receiver. As a result, prior to the 1930's, the designers of electrical circuits and systems typically needed only to insure that their devices would function in the presence of natural noise sources such as lightning or sunspots and started designing immune systems to external interference.

In 1933, the international committee for radiated emissions, better known as CISPR was founded to deal with the increasing emerging problems of EMI. Through the 2nd World War knowledge of electromagnetic waves and their ability to create disturbances was used [14]. During the war, radar technology was developed. Not only did the new communication technologies of radio, television and telephone require electromagnetic compatibility, they were the driving force in changing from tube technology to transistors. The evolution of highly integrated chip technologies requires a broad understanding and use of EMC design experience [16].

Late in the 60's, concrete investigations were made to deal with the immunity of electrical products. And in 1973 the International Electrotechnical Commission, the IEC, founded the technical committee TC77 whose function is to develop standards related to EMC, to take in account the rising EMC problems with the emerging of digital circuits' technology.

In 1979. The Federal Communications Commission, FCC in the USA imposed legal limits on the electromagnetic emissions from all digital equipment. These limits were imposed as a result of the growing availability of digital systems including small calculators and forms of digital equipment that were interfering with wired and radio communications and broadcast systems [14].

A further major step forwards was taken in the 1980s by the European Community. They introduced what was termed a new approach to standardising EMC requirements to enable trade of electronics equipment to be undertaken more freely [23].

Since 1980, over 30 years, as the technology progressed, legislation and standardization was developed to insure the harmony of the new sciences from an EMC standpoint in Europe, USA as well as in other countries all over the world. And each new generation of engineers and technicians are again challenged by the issue of EMC with each new product and within each new installation.

## IX. 3. Types of Standards

### IX. 3. 1. International standards

The International Electro-technical Commission (IEC) prepares international standards for all electrical, electronic and related technologies, and the International Organization for Standardization (ISO) prepares international standards for all technologies other than electrical and electronic technologies. However, European countries often take the initiative in proposing the standards and establishing them as ISO/IEC international standards. These standards interact mutually with all existing worldwide standards to ensure an optimal regulation for the international market [24].
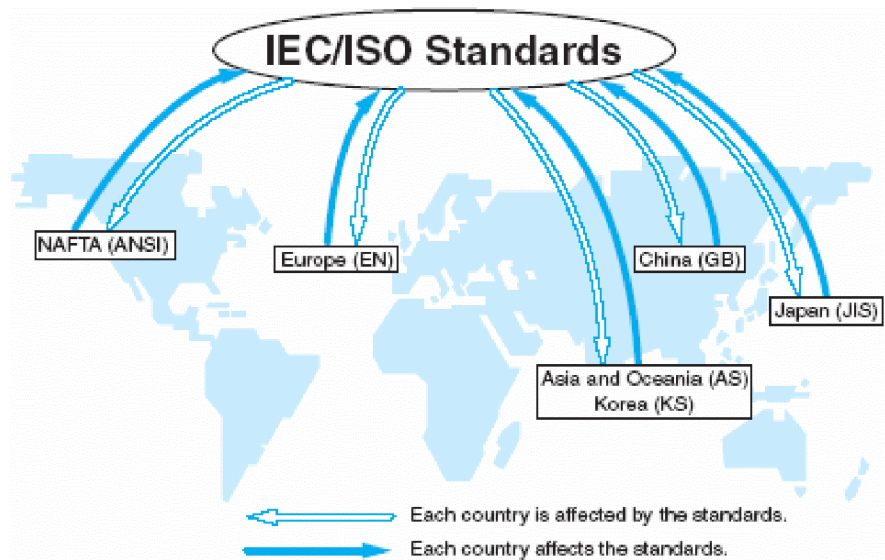


***Fig.I.10:*** *The interaction between the worldwide standards organizations and the IEC/ISO standards [24]*

Technically, two IEC technical committees are devoted full time to EMC work, although nearly forty others have some involvement with EMC as part of their scope. The two full time committees are TC77, Electromagnetic compatibility between equipment including networks, and the International Special Committee on Radio Interference or CISPR, which is the acronym for its French title. Co-ordination of the IEC's work on EMC between the many committees involved is the responsibility of the Advisory Committee **on** Electromagnetic Compatibility ACEC, the Advisory Committee on

EMC, which is expected to prevent the development of conflicting standards. [25] The importance of the IEC standards is that they may either be transposed directly into harmonized EN standards, in which case they become applicable for the self-certification route, or they may be referred to by product-specific or generic harmonized standards.

## IX. 3. 2. TC77

The TC77 has been characterized as "The United Nations for EMC" [26]; certainly it attempts to cover most aspects of the subject on a worldwide basis. The structure of TC77 is a large and influential group, and liaises with several other product-related committees within IEC including CISPR, as well as with outside bodies such as CENELEC, ITU and several electric power related groups.
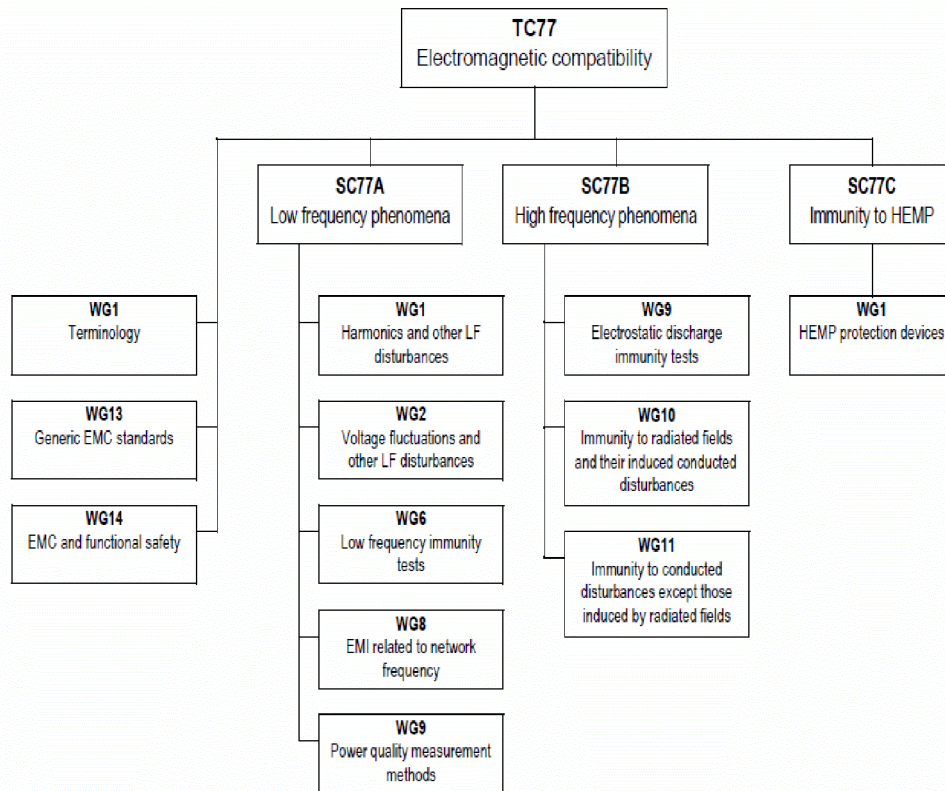


**Fig.I.11:** *IEC TC77 structure*

The major output of TC77 now is the various parts of IEC Publication 61000 for Electromagnetic Compatibility. This document has been published in stages incorporating all non-CISPR and non-product specific EMC material [16].

## IX. 3. 3. European standards

The first work in the EMC field in Europe can be traced back to when the International Special Committee on Radio Interference CISPR (now part of the IEC) was established in 1934. But today the scope of EMC work has expanded to such an extent that the IEC organizes it among several committees. Many of these have working relationships or official liaisons with outside groups ranging from professional associations to national, regional and international organizations. Actually, nowadays all the European Standards are issued from CEN/CENELEC, where, More than eighty percent of the adopted European standards are identical to or based upon corresponding international standards [27]. These standards numbering is usually prefixed by EN.
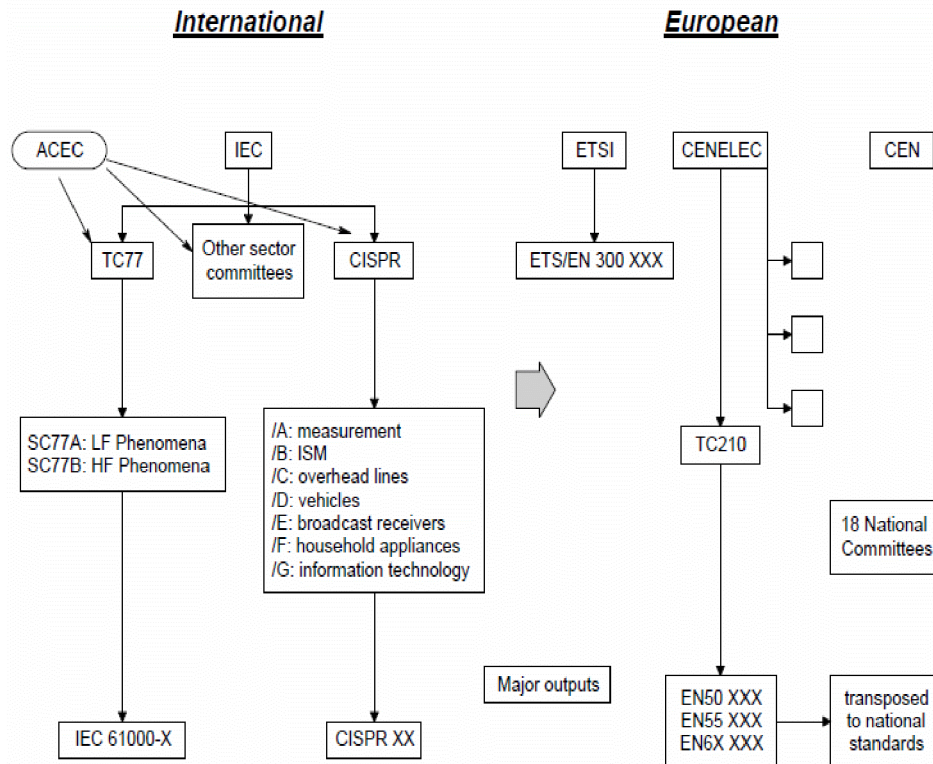


***Fig.I.12:*** *IEC and CISPR Standards structures.*

## IX. 3. 4. CE Marking

The CE Marking is a mark of EMC compliance with the European Community Directives. The CE Marking indicates that the product complies with the stipulated level of EM compatibility in all relevant European

Community Directives [16]. The CE Marking is considered as the product passport to be imported and exported to Europe without restriction.



**Fig.I.13:** *CE Marking in European standardization.*

All electrical/electronic devices should satisfy both the European community Directives and European Norms (EN) to be liable for CE marking. EN Standards complement the EC Directives; and satisfying the EN Standards alone, however, does not result in the EC Directives being satisfied. Countermeasures for product liability are generally required in manuals and catalogs.

## IX. 3. 5. NATIONS STANDARDS

Most nations are represented in the international standards process by a national organization. These national organizations can adopt and follow international standards, adopt and follow standards provided by their regional standards bodies, and/or prepare standards (or accredit qualified organizations to prepare them) as needed within their own country. For instance:

- ✓ British Standards Institution (BSI).
- ✓ American National Standards Institute (ANSI) and USA Federal Communications Commission (FCC) .
- ✓ Canada standards.
- ✓ Australian and New Zealand regulations.
- ✓ China standards (CB).
- ✓ Japan standards (JIS).
- ✓ Korea standards (KS)

However, some nations have chosen not to develop their own set of standards, but instead contribute to and use the international standards of the ISO and IEC [16].

## IX. 3. 6. Basic standards

Describe the general and fundamental rules for meeting the requirements. Terminology, phenomena, compatibility levels, measurement, test techniques and classification of EM environments are so described within. The EN 61000-4-x series of standards which cover almost all the EMC aspects are the best known examples of basic standards [28].

## IX. 3. 7. Generic standards

Refer to specific environments. They set minimal EMI levels which equipment in these environments must meet. Where no product standards exist then the generic standards are to be used. Generic standards describe household and industrial EMI environments [28]. Examples of generic standards are EN 61000-6-1/2/3/4. These standards are usually coordinated with the products one.

## IX. 3. 8. Products standards

Products standards are established for specific products or product groups. These standards are coordinated with the generic standards which can be used for the test of the product if no specific standard for this product exist [28].

# X. BASIC CISPR EMC STANDARDS

CISPR 16 is a series of standards and is published under the general title Specification for radio disturbance and immunity measuring apparatus and methods [29, 30].
- CISPR 16-1-1 Measuring apparatus
- CISPR 16-1-2 Ancillary equipment – Conducted disturbances
- CISPR 16-1-3 Ancillary equipment – Disturbance power
- CISPR 16-1-4 Ancillary equipment – Radiated disturbances
- CISPR 16-1-5 Antenna cal. test sites for 30 MHz to 1 000 MHz
- CISPR 16-2-1 Conducted disturbance measurements
- CISPR 16-2-2 Measurement of disturbance power
- CISPR 16-2-3 Radiated disturbance measurements
- CISPR 16-2-4 Immunity measurements

- CISPR 16:3-x Reports and recommendations, further information and radio disturbance in general are given.
- CISPR 16:4-x Information related to uncertainties, statistics and limits.

# XI. BASIC STANDARDS IEC 61000 FOR EMC

There are several parts of IEC 61000. This section only considers those parts which are directly relevant for testing equipment. Where, for instance, Part 1 consists of general purposes about the safety function and integrity of equipments. Part 2 (The EM environment) is useful for understanding the many environmental aspects of EMC but does not specify tests. Part 4 specify the EMC test and measurement techniques. Note that the European equivalent number of any IEC standard is obtained by writing EN 6XXXX instead of IEC 6XXXX. The standards are (mostly) technically equivalent, but the European versions have an additional foreword which specifies how the standard is to be applied for certification purposes [16].

*Tab I.1: Basic standards IEC 61000 for EMC [31].*

**IEC 61000**

**Part 1: General**
- the safety function requirements (what the function does); and
- the safety integrity requirements (the likelihood of a safety function being performed satisfactorily).

**Part 2: Environment**
- Description of the environment
- Classification of the environment
- Compatibility levels

**Part 3: Limits**
- Emission limits
- Immunity limits (insofar as they do not fall under the responsibility of product committees)

**Part 4: Testing and measurement techniques**
- Measurement techniques
- Testing techniques

**Part 5: Installation and mitigation guidelines**
- Installation guidelines
- Mitigation methods and devices

**Part 6: Generic standards**

**Part 9: Miscellaneous**

# XII. GENERIC EMC STANDARDS

CENELEC gave a high priority to developing the Generic Standards. These are standards with a wide application, not related to any particular product or product family, and are intended to represent the essential requirements of the Directive [16]. They are divided into two standards, one for immunity (EN 50 082) and one for emissions (EN 50 081), each of which has separate parts for different environment classes:

- IEC 61000-6-3 Generic Emission Standard for residential, commercial and light –industrial environment.
- IEC 61000-6-4 Generic Emission Standard for industrial environment.

# XIII. EMC TESTING

The aim of the EU directive (and FCC rules in the US) is to ensure that all emissions are kept low, and all immunity levels are kept high, for any electrical/electronic devices; thus creating a wide safety margin so ensuring problems are avoided. This is the principle of Electromagnetic Compatibility (EMC). Products that are declared compatible with this principle are EMC Compliant. In order to be able to confirm that EMC compliant specific tests (in particular for immunity issues) are required for all devices according to the nature of the product function [32]. These tests are governed by a set of standards specific to each situation for emission (conducted and radiated) and for immunity.

## XIII.1. EMISSION TEST STANDARDS

CISPR is in the origin of the basic international emission standards which are adopted by national authorities. Most common tests perform measurements for conducted disturbances (from 150 KHz to 30 MHz), and for radiated disturbances (from 30 MHz to 1GHz), these standards are mainly: [33]

EN 55011/CISPR 11: Industrial, scientific and medical (ISM) radio-frequency equipment – Electromagnetic disturbance characteristics – Limits and methods of measurement for both conducted and radiated emission.

EN 55022/CISPR 22: Radio disturbance characteristics - Limits and methods of measurement (conducted and radiated emission).

## XIII.2. IMMUNITY TEST STANDARDS

Immunity tests are designed to ensure that the product will work as specified in a typical environment. During any EMC immunity test, the operation of the device must be monitored and any degradation in performance should be noted. However, there are several types of immunity tests, and each one of them is covered by an IEC specific standard. They actually represent the basic IEC 61000 standards set [16].

| Immunity | | | | | |
|---|---|---|---|---|---|
| Pulsed | Power quality | H Field | Conducted LF | Conducted RF | Radiated RF |
| ESD<br>EFT/ Burst<br>Surge | Dips<br>Ring wave<br>Harmonics<br>V. fluctuation<br>Ripple an DC<br>Oscil. wave<br>Unbalance<br>Freq. variation | Power freq.<br>Impulse<br>Damped sine | DC, 15 Hz -<br>150 kHz<br>up to 300 V,<br>2 - 150 kHz DM | 150 kHz -<br>80 (230) MHz<br>1, 3, 10 V EMF<br>80% AM 1 kHz | 80 MHz -6 GHz<br>3, 10 V/m<br>80% AM 1 kHz |
| EN 61000-4-2<br>EN 61000-4-4<br>EN 61000-4-5 | EN 61000-4-11<br>EN 61000-4-12<br>EN 61000-4-13<br>EN 61000-4-14<br>EN 61000-4-17<br>EN 61000-4-18<br>EN 61000-4-27<br>EN 61000-4-28<br>EN 61000-4-29<br>EN 61000-4-34 | EN 61000-4-8<br>EN 61000-4-9<br>EN 61000-4-10 | EN 61000-4-16<br>(EN 61000-4-19) | EN 61000-4-6 | EN 61000-4-3<br>EN 61000-4-20<br>EN 61000-4-21<br>(EN 61000-4-22) |

*Fig.I.14:* EMC immunity test standards [34].

In this our study we interest in particular to immunity test concerned by the radiated RF energy applied to a small EUT inside a GTEM cell and the

application target is of biomedical nature concerned by electrocardiogram signal for portable device (even supporting life) for emergency, domestic, ambulatory health care. Thus, the standards we are using here are the EN 61000-4-3 [35] for immunity test to radiated EM energy, EN 61000-4-20 [36] for the use of GTEM cell, and the EN 60601-1-2 [37] for EMC requirements for Medical equipments, which are described as follow:

# XIV. EN 61000-4-3

### TITLE OF THE STANDARD

Electromagnetic compatibility (EMC) -Part 4-3: Testing and measurement techniques -Radiated, radio-frequency, electromagnetic field immunity test.

### TESTS REQUIREMENTS

Radiated RF field generated by antennas in a shielded anechoic enclosure using the substitution method (pre-calibrated field), swept from 80MHz to 1000MHz at slower than $1.5 \times 10 \text{-} 3$ decades/s, or with a step size not more than 1% of fundamental and dwell time sufficient to allow the EUT to respond. Eight (twelve) tests are needed, one in each polarization with the antenna facing each of the four sides of the EUT (and top and bottom if these might be affected). Field uniformity within –0/+6dB over 12 out of 16 points within a 1.5 x 1.5m square area at the front face of the EUT is required of the chamber Alternative methods such as a stripline or TEM cell can be used provided that field homogeneity requirements are met and that the EUT and wires can be arranged as specified Amendment A1: 1998 has revised the field uniformity calibration method and added testing from 1.4 to 2GHz

### TEST LEVELS

Severity levels of 1, 3 or 10 V/m unmodulated (or greater) depending on the expected EMR environment; the actual applied signal is modulated to 80% with a 1 kHz sin wave.

# XV. EN 61000-4-20

Electromagnetic compatibility (EMC) - Part 4-20: Testing and measurement techniques - Emission and immunity testing in transverse electromagnetic (TEM) waveguides.

## Scope of the standard

This standard relates to emission and immunity test methods for electrical and electronic equipment using various types of transverse electromagnetic (TEM) waveguides. It does not intend to specify the tests to be applied to any particular apparatus or system(s). The main intention of this standard is to provide a general basic reference for all interested product committees of the IEC. For radiated emissions testing, product committees should select emission limits and test methods in consultation with CISPR standards. For radiated immunity testing, product committees remain responsible for the appropriate choice of immunity tests and immunity test limits to be applied to equipment within their scope. This standard describes test methods that are separate from those of IEC 61000-4-3.

## GTEM Use requirements

The object of this standard is to describe:

- TEM waveguide characteristics, including typical frequency ranges and EUT-size limitations;

- TEM waveguide validation methods for EMC tests (including the calibration);

- The EUT (i.e. EUT cabinet and cabling) definition;

- Test set-ups, procedures, and requirements for radiated emission testing in TEM waveguides and

- Test set-ups, procedures, and requirements for radiated immunity testing in TEM waveguides.

# XVI. Medical electrical equipment

## EN 60 601-1-2: Emissions and immunity

### Title of the standards

Medical electrical equipment – part 1: General requirements for safety – 2. Collateral Standard: Electromagnetic compatibility – requirements and tests

### Scope of the standard

Medical electrical equipment and systems, information technology equipment used in medical electrical application This standard defines the general EMC requirements and tests for such equipment; requirements for particular classes of equipment are or will be contained in the particular requirements of part 2 of this standard, which is fundamentally a safety standard. NB it has been withdrawn as a harmonized standard for the EMC Directive, since EMC of medical electrical equipment is now covered by the Medical Devices Directive and not the EMC Directive; this standard is only harmonized for the MDD [16].

### Tests requirements

RF emissions: as for CISPR 11 [38] (EN 55011) with some modifications. Class A equipment is allowed in domestic establishments when used under the jurisdiction of a health care professional.

ESD: 3kV contact, 8kV air discharge to IEC 801-2.

RF Radiated: 3V/m, amplitude modulated from 26MHz to 1GHz according to IEC 801-3 second edition. This provision is causing some problems since there is in fact no second edition of IEC 801-3, and the standard that should have been referred to (IEC 61000-4-3 [35]) specifies tests for 3 or 10 V/m(supporting life devices) from80 MHz–2 GHz with 2HZ amplitude modulated sinewave. For other than life support equipment, RF immunity need only be tested at the ISM frequencies.

ELECTRICAL FAST TRANSIENTS: 1kV for plug-connected mains ports, 2kV for permanently installed equipment, 0.5kV for interconnecting lines longer than 3m, as per IEC 801-4.

SURGE: 1kV differential mode, 2kV common mode, at the mains port, as per IEC 801-5 (now IEC 61000-4-5 [39]).

# XVII. BIBLIOGRAPHY

[1] Henry W. Ott.; "Electromagnetic Compatibility Engineering"; ISBN 978-0-470-18930-6, 2009.

[2] Frank Leferink et al;" Vision 2020: THE EMC TECHNOLOGY ROADMAP"; European Technology Network; TOWARDS A SUSTAINABLE ELECTROMAGNETIC ENVIRONMENT; April 2006.

[3] Crowell, B. (2007). *Simple nature*. Fullterton, California: Light and Matter.

[4] Bo Thidé.; "Electromagnetic Field Theory"; second edition; ISBN: 978-0-486-4773-2; 1997-2011.

[5] Mardiguian, M. (2001). *Controlling radiated emissions by design*. Norwell, Massachusetts: Kluwer Academic Publishers.

[6] Sadiku, M. N. O. (2007). *Elements of electromagnetics*. New York: Oxford University Press.

[7] http://www.astrosurf.com/luxorion/qsl-em-radiation.htm

[8]"Natural sources of electromagnetic radiation: cosmic sources". York University Educational ScienceNet website. Obtained online at http://resources.yesican.yorku.ca/trek/radiation/final/index_natural_waves.html

[9] Safa Haddad. "Cutting out interference in electromagnetics". Malaysia Times. 2 Apr 1995. Science section, p.34.

[10]Gordon Holman and Sarah Benedict. "What is a solar flare?". NASA/Goddard Space Flight Center Laboratory for Astronomy and Physics website. Obtained online at http://hesperia.gsfc .nasa.gov/sftheory/flare.htm.

[11] Federal Communications Commission. "Interference". U.S. FCC Consumer and Governmental Affairs Bureau website. Obtained online at http://www.fcc .gov/cgb/consumerfacts/interference.html.

[12] http://www.epa.gov/radiation/understand/ionize_nonionize.html

[13] International Electro-technical Commission. Electropedia: The World's Online Electro-technical Vocabulary. Term: Electromagnetic compatibility. Website, February 2008 :http://www.electropedia.org/

[14] Paul, Clayton R. "Introduction to electromagnetic compatibility"; 2nd edition; ISBN-13: 978-0-471-75500-5; ISBN-10: 0-471-75500-1; 2006.

[15] Mark I. Montrose, EMC and Printed Circuit Board Book, IEEE Electromagnetic Compatibility Society, 1999.

[16] Tim Williams; "EMC for Product Designers"; third edition; ISBN: 0 7506 4930 5; 2001.

[17] Learn EMC: http://www.learnemc.com/tutorials/

[18] http://www.radio-electronics.com/info/circuits/emc-emi/electromagnetic-interference-basics-tutorial.php

[19] Tim Williams; Keith Armstrong: "EMC for Systems and Installations"; Newnes; ISBN 0 7506 4167 3; 2000.

[20] Joseph J. Carr: "DECIBELS"; Universal Radio Research 6830 Americana Parkway Reynoldsburg, Ohio 43068.

[21] EMC/test/immunity:http://www.elliottlabs.com/services_emc_immunity.htm

[22] http://www.emtest.com/what_is/emv-emc-basics.php.

[23] http://www.radio-electronics.com/info/circuits/emc-emi/standards-legislation.php.

[24] http://www.omron.com.au/technical_guide/safety_component/safety_requirements.asp.

[25] R Kay, IEC, IEE 7th International Conference on EMC; "Co-ordination of IEC standards on EMC and the importance of participating in standards work"; , York 28-31st Aug 1990, pp 1-6.

[26] D Möhr ;"IEC TC77 EMC: "The United Nations" for EMC"; EMC Europe 2000, 4th European Symposium on EMC, Brugge, September 11-15 2000.

[27] http://www.iec.ch/emc/iec_emc/

[28] CWS Company, Application Note, Understanding EMC Standards and Specifications.

[29] A Guidance for users of the CISPR Standards; www.google.co.uk

[30] Gideon Wiid, Paul van der Merwe; "IEC and CISPR Standards"; 2007.

[31] http://www.iec.ch/emc/basic_emc/basic_61000.htm.

[32] http://www.elliottlabs.com/services_emc_immunity.htm

[34] http://www.laplace.co.uk/

[35] EN 61000-4-3: Electromagnetic compatibility (EMC) -Part 4-3: Testing and measurement techniques -Radiated, radio-frequency, electromagnetic field immunity test.

[36] EN 61000-4-20: Electromagnetic compatibility (EMC) - Part 4-20: Testing and measurement techniques - Emission and immunity testing in transverse electromagnetic (TEM) waveguides.

[37] EN 60601-1-2: Medical electrical equipment – part 1: General requirements for safety – 2. Collateral Standard: Electromagnetic compatibility – requirements and tests.

[38] EN 55011/CISPR 11: Industrial, scientific and medical (ISM) radio-frequency equipment – Electromagnetic disturbance characteristics – Limits and methods of measurement for both conducted and radiated emission.

[39] IEC 61000-4-5: Electromagnetic compatibility (EMC) – Part 4-5: Testing and measurement techniques – Surge immunity test.

# CHAPTER II:

# FIELD PROGRAMMABLE ANALOG ARRAYS (FPAA)

## I. INTRODUCTION

The trend in modern VLSI circuit design is to increase the level of integration, decrease power consumption and the time to market, and reduce the cost of products. The key concept for this is to use a single hardware implementation for more than one type of system by reprogramming it for different systems; this type of concept is actually based on the philosophy of the possibility of re-configuring and reprogramming these devices as much as needed. Indeed, this need for programmability and re-configurability has led to invent a specific category of circuits called field-programmable arrays devices. which offer a high flexibility of re-programmability and re-configurability , and a fast prototyping process, using PC-based design tools, which facilitate the designers task, and reduce the level of expert knowledge required to build working ICs [1].

Nowadays, most of the electronic systems (for: communications, biomedical applications, security application, navigation and aerospace applications...etc) contain both analogue and digital circuits. These systems are supposed to be able to deal with physical nature of signals (analogue signals), and to deal with treating them in the digital world (processing signals). Hence by that, the need for different topologies of Programmable circuits (digital and analogical). In fact, this has resulted in the emergence of field programmable gate arrays (FPGA) for digital applications, and the field-programmable analogue arrays (FPAA) for the analogue part. Over more than 60 years, the FPGA technology has been very well established to make a whole system fully programmable and reconfigurable. On the other side, carrying a similar technology for the analogue part was difficult and still needs some improvement. Due to their sensitivity to noise, cross-coupling, process and temperature drifts. This makes the changing of their parameters and functionality without degrading the system performance a very difficult task. However, in the last 20 years reconfigurable analogue circuit has been introduced called field-programmable analogue arrays (FPAA) [2–6]. And the work is in present intense on the development of field-programmable mixed-signal array (FPMA) [7].

In signal-processing applications, analogue ICs requires a smaller chip area and has lower power consumption. Programmable analogue circuits are advantageous for wireless and portable applications where compactness and low-power consumption are important. Here, FPAAs offer not only rapid prototyping IC, but also high suitability to be used for high bandwidth applications (communication) and very small frequencies applications (biomedical). Which prove that FPAAs are very useful tool for the design of working analogue and mixed-signal ICs, where they help to reduce the complexity of digital circuit design [8]. In fact, the FPAA application range spans most electronic areas including data acquisition and control, automation, robotic, instrumentation and telecommunications.

Historically speaking, the first field-reconfigurable IC intended primarily for synthesis and test of analogue neural-network architectures reported in [2]. Where, CMOS transmission gates were used as the active switch elements that connected basic resources such as differential pairs and current mirrors in a hierarchical routing network on board memory (SRAM) was provided for storing the state of each switch element [1]. However, with the evolution of field-reconfigurable IC architectures, other kind of interesting applications were taking place, particularly in filters design in mixed-signal and RF circuits, like the high frequency analogue filters used in achieving ubiquitous communication and computing, the high Q band pass filters used in wireless communications, or, the Linear phase filters/equalisers at higher frequencies used in mass storage systems such as computer hard disk drives [1].

In reality, depending on the internal architecture of the FPAA, Common analogue signal processing functions such as offset removal, rectifiers, gain stages, comparators and first-order filters can be implemented using just one Configurable Analog Block (CAB). However, more complex functions such as high-order filters, oscillators, pulse-width modulators and equalisers can be implemented using two or more CABs. And more complex functions require more than one FPAA some times. Besides its flexibility of configuration for several times (non limited), the FPAA is also a very low consumption circuit and a low cost chip. Those characteristics makes it very suitable candidate for front end applications, in particular for those

concerned by biomedical field where the front end stage in any electronic system is very crucial for the well performing of the rest of the system stages, and where the use of digital circuits still have some issues like data losses. The use of FPAA in the implementation of different applications concerned by biomedical signals have been widely explored within the last ten to thirteen  years, where the contribution of the FPAA in these implementations was spanning between the whole signal conditioning system and only one specific element like amplifier or filter. These biomedical devices involving the FPAA circuit are usually used as a part of telemedicine system, homecare or emergency systems and even for monitoring implantable systems. In most of these applications, usually the FPAA is used together with the FPGA into the same system.

## II. Field Programmable Analog Array (FPAA) overview

Field programmable analog array FPAA are large scale integrated circuits built in CMOS technology, similar to the FPGA (Field Programmable Digital Array) one, with preserving the several orders of magnitude of power saving typical of analog signal processing [8, 9], they can be efficiently programmed and reprogrammed to perform a large number of analog circuit functions, from the basic one like simple amplification to more complicated ones like conditioning signal systems. The FPAA appeared for the first time in 1980's, reached the market in 1996', and have been commercialized for the first time as Anadigm FPAA technology in 2000[10].
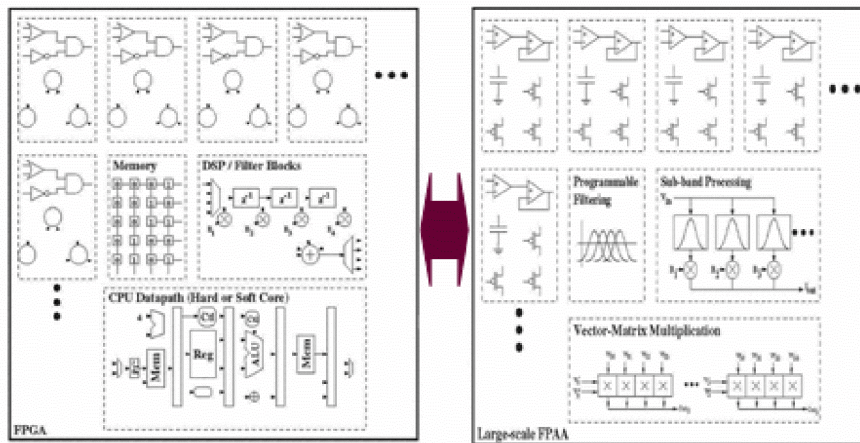


*Fig.II.1*: Illustration of the difference between FPGA and FPAA circuits (basic structure and principal of working).

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## III. Field Programmable Analog Array (FPAA) architecture

As shown in Fig.II.2 the basic architecture of an FPAA circuit is composed of a matrix of configurable analog blocks (CABs) connected with each others by the programmable interconnections network; the set composed of CABs blocks and interconnections network is rounded by input/output blocks which insure the communication of the circuit with the external world. It contains also memory registers used in digital programming and a set of elements which can be associated to the Input/output blocks to improve better interfacing with the external world as buffers, anti aliasing and smoothing filters [11].
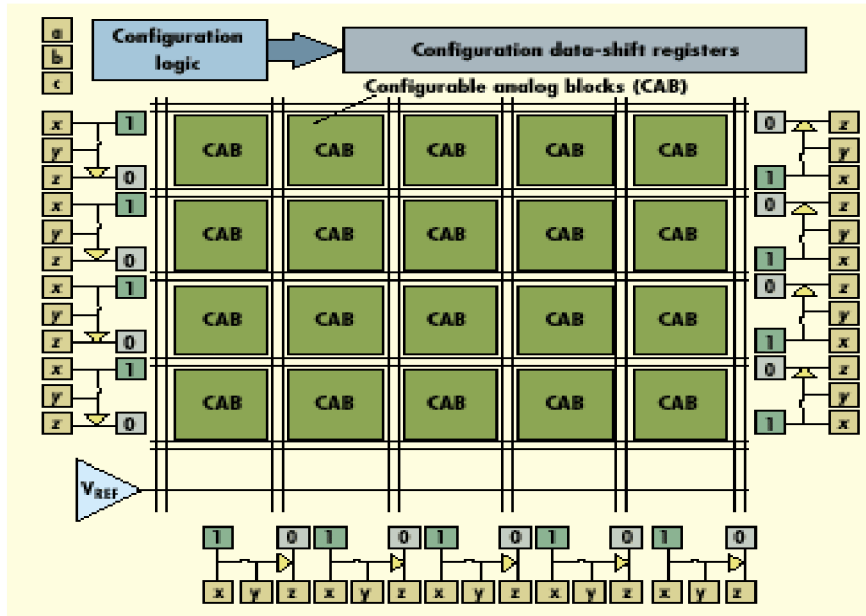


*Fig.II.2:* *FPAA architecture schematic.*

The interconnections in an FPAA circuit are based on the switched capacitors (SC) technique [12], in which a set of capacitances can emulate the resistance behaviour and provide a very good accuracy. This technique is used to establish the communication between different configurable blocks (CABs) into the chip in order to answer a specific configuration. In fact, this technique provides the FPAA with the capability of imitating a wide variety of circuits as amplifiers, filters, integrators and even a full scale analog signal processing circuit [5]. In addition, a modern FPAA contains

analog to digital converters (ADCs) and digital to analog converters (DACs) that give more flexibility to the FPAA, and make it very suitable for interfacing easily physical sensors or analog systems with digital ones. The programmability feature of configurable analog blocks is done by the user programmable switches placed in the signal paths when crossing the network of interconnections.

Since the first development of this type of circuit and still in the present, lot of approach have been developed, to improve better connections and less currents loses. Actually, the adopted technology in the present commercialized FPAA circuits is the switched capacitor (SC) technique, since it is the less expensive technique which provides the FPAA with a good degree of accuracy and more flexibility to imitate a wide number of circuits.

## III.1. CAB's STRUCTURE

Actually, the sources of each configurable analog blocks, varies between different commercialized FPAAs circuit and between their different circuit's generations. A typical (CAB) contains two op-amps with local and global feedback loops, a comparator, banks of programmable capacitors, current conveyers and a collection of configurable routing and clock resources [13] as shown in Fig.II.3. The programming of the CAB is achieved by programming the combination of the different capacitors to connect the necessary elements for the desired function by determining the ratio of the programmable capacitors employed, and to determine whatever is an inverted or a non inverted function.
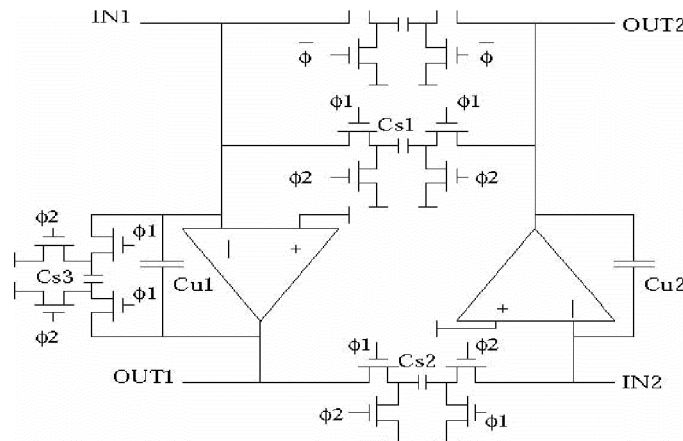


*Fig.II.3: The configurable block (CAB)*

All signal processing within the CABs is fully differential to provide higher fidelity of the signal. The more the FPAA contains CABs the more it is flexible and the more it can contain more complicated applications.

## III.2. INTERCONNECTION NETWORK

The communication among CABs or among CABs and input/output blocks in the FPAA circuit is achieved by an interconnection network based on switched capacitors (SC) technique, this network is composed of capacitors and MOSFET transistors as shown in Fig.II.4.
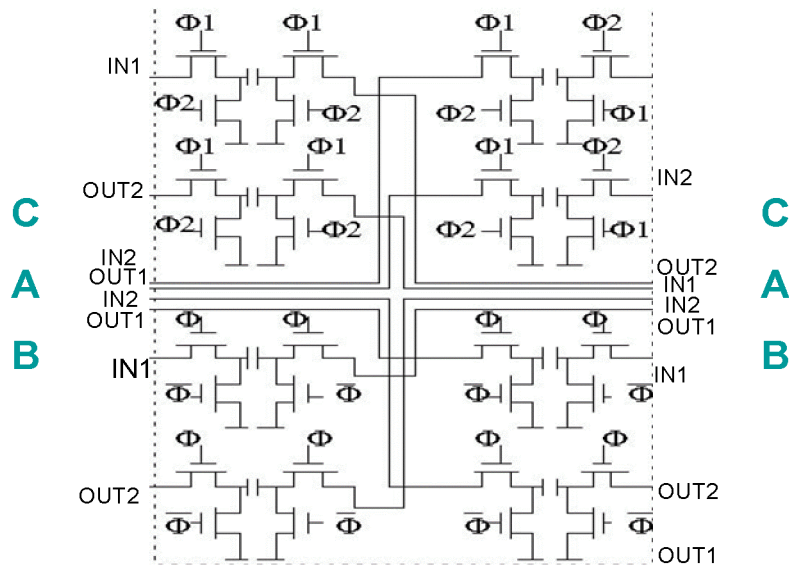


*Fig.II.4*: *Example of interconnection bloc schematic.*

The switched capacitor technique is based on the realization that a capacitor switched periodically between two circuit nodes (as shown in Fig.II.5) is equivalent to a resistor connecting these nodes if we are interested in an average value of current over a period of time exceeding a number of times the switching period.
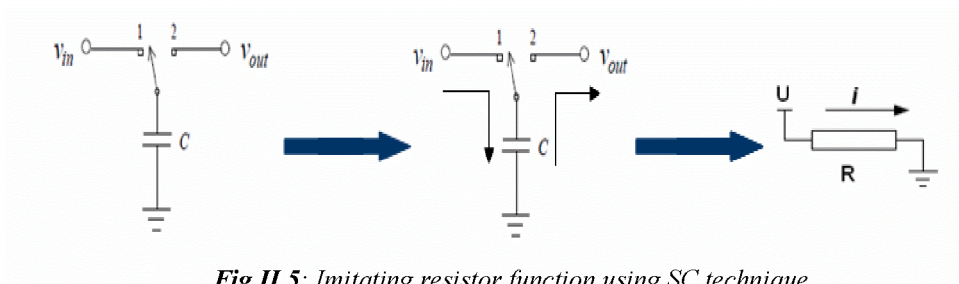


*Fig.II.5*: *Imitating resistor function using SC technique.*

During the time when the switch is in position 1, the capacitor is charged to the voltage applied to the input, Vin. So the total charge on the capacitor C is $Q_1 = C$ *Vin*, in steady state. When the switch changes to position 2, the new charge on the capacitor for the steady state will be $Q_2 = C$ *Vout*. The net charge transferred from the input to the output during one switching period is then:

$$\Delta Q = Q_1 - Q_2 = C\left(V_{in} - V_{out}\right)$$

This is equivalent to a current *I* flowing from the input to the output:

$$I = \frac{\Delta Q}{T} = \frac{C\left(V_{in} - V_{out}\right)}{T}$$

And from this equation we can easily calculate an equivalent resistor value:

$$R = \frac{T}{C} = \frac{1}{C \cdot f}$$

Where, R is the ratio of the period (T) of the clock in the FPAA circuit and the capacitor value obtained by the configuration (C) [14]. The equivalent resistor can be obtained by the alternatively switching the input/output of the capacitor. Fig.II.5. this switched capacitor configuration can be programmed to be a capacitor, positive resistor, or negative resistor. This technique provides the FPAA with lot of advantages than any other technique, like obtaining batter resistor value, obtaining better tolerance and matching, and a high voltage linearity.

When establishing a connection, capacitors should be switched or un-switched, depend of the function desired. For instance, the capacitors input/output are switched to insure the summation of two signals at a node, and they should be un-switched to insure the realization of a finite transmission zeros. It is important to note that, the number of interconnection into the FPAA is limited.

Actually, Switched capacitor circuits operate as time-discrete signal processors without the use of A/D or D/A converters. As a result, these

circuits are most easily analyzed with the use of z-transform techniques. Typically, anti-aliasing and smoothing or reconstruction filters are required.

Especially for filtering, switched capacitor circuits have become extremely popular due to their accurate frequency response as well as good linearity and dynamic range. Accurate discrete-time frequency responses are obtained since filter coefficients are determined by capacitor ratios which can be set quite precisely in an integrated circuit (in the order of 0.1 percent). Such accuracy is orders of magnitude better than that which occurs for integrated RC time. Once the coefficients of a switched capacitor discrete-time filter are accurately determined, the overall frequency response remains a function of the clock frequency. Fortunately, using crystal oscillators, clock frequencies can be set very precisely [15].

## III.3. FPAA TIME BASE

The FPAA operation is governed by a clock signal, and its configuration determines the clock input which will be used as the master clock. Actually, the master clock in the FPAA configuration is divided into five domains. The first one is appropriate to the chopper stabilized amplifiers associated to the input/output cells. The chopper stabilized amplifiers reduces greatly the input offset voltage normally associated with op-amps. This can be very useful for applications where the incoming signal is very weak and requires a high gain amplifier at the input (as in biomedical applications). The four other domains are used as pre-scalar which feed four programmable dividers that can be used by the designer according to the application needs.

## IV. FPAA CHARACTERISTICS AND EVOLUTION

### IV.1. CHARACTERISTICS

As previously mentioned, FPAAs are a wide range of potential applications for programmable analogue systems, including low-power computing [16], remote sensing [17], and rapid prototyping [18]. According to [19], the characteristics of programmable analogue architectures in regard to the FPAA implementation can be defined using different classifications. Some of them are:

### IV.1.1. PROGRAMMING CAPABILITY

A circuit can be classified according to how many times it can be programmed into two classes:

1. Circuit which are programmable only once, like the case of fused or anti-fused architectures circuits [20].

2. And metal-mask programmable analogue arrays, which allow several (possibly infinite) reconfigurations, like switched-capacitor circuits [21] the case of FPAAs, and cellular neural networks machines proposed by Tamás Roska and Leon O.Chua in 1993 [22].

### IV.1.2. PROGRAMMING METHOD

The programming method classification defines the way of changing the circuit internal parameters to obtain desired system behaviour. These changing can be obtained by:

1. Direct programming, where the designer or designer tool has the detailed knowledge of the signal flow [5], and the changing can concern the implementation structure or only some blocks parameters.

2. Learning and adapting techniques, where the system is seen as a "black box". Usually, this method is achieved using genetic algorithms [23, 24] and neural networks [25, 26].

### IV.1.3. STRUCTURE FLEXIBILITY

A system can also be characterized according to its versatility. Some architecture's allow only their parameters to be programmable, while other systems allow the signal path to be changed [27], by changing the interconnection of different circuits.

### IV.1.4. GRANULARITY

The basic idea behind FPAAs is the use of basic units (CABs) to implement a range of functions. In general, the complexity of these basic blocks is a trade-off between performance and flexibility. The block complexity can range from:

1. Fine granularity, where the basic blocks are basic components, like transistors, resistors and capacitors [17],

2. Coarse granularity, with more complex circuits like capacitively coupled current conveyors [8],

3. And vector-matrix multipliers [8].

## IV.1.5. Signal representation

Signals need some sort of physical representation to be processed by electronic circuits. Analogue circuits are defined as operating in one or more domains, usually voltage, current or charge domain. Voltage domain is the classical choice for analogue engineers, but current and charge techniques have their common applications, like power control and CCD image sensors, respectively. Recently, timing has been used as another possible representation.

Other FPAA characteristics can be used to define other classifications. For instance, signal timing characteristics employed, by using discrete or continuous time circuitry [28, 29];

## IV.1.6. Discrete-time FPAAs

Discrete-time FPAAs are typically switched-capacitor designs. With this based architecture, the incoming voltage is sampled by opening and closing a switch that connects the input to an initial capacitor (Fig II.6). The switch and capacitor form a type of analog register, and the system's signal path is partitioned by these registers. The basic computational elements are usually operational amplifiers and analog registers, which synthesize a linear resistor; the resistor value is determined by the switching rate and capacitor value.
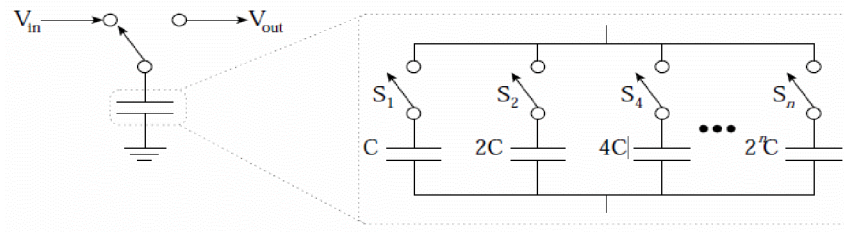


*Fig.II.6*: *switched capacitor principle working in discrete time FPAAs*

The synthesis of linear variable resistors gives switched-capacitor FPAAs high flexibility. However, this class of FPAAs can be hard to design proficiently, since the switches and capacitors can introduce noise and nonlinearities into the system that must be overcome [30]. In addition, these designs have a limited bandwidth based on the sampling rate, are complicated by the need for continuous-time anti-aliasing and reconstruction filters at the input and output, and can be large if programmable capacitor arrays are included [30, 31]. Nevertheless, Switched-capacitor designs are not the only discrete-time FPAAs. Switched-current circuits can also be used to build an FPAA. The advantages of this technique include not requiring operational amplifiers, capability of fabrication on standard digital CMOS processes, and elimination of distortion on the signals due to parasitic resistances. To their detriment, these designs can produce less accuracy than switched-capacitor circuits, and since the signals are all currents, a given output stage can drive only one input stage [32].

## IV.1.7. CONTINUOUS-TIME FPAAS

Continuous-time FPAAs classically use an array of fixed components (often operational amplifiers and/or transistors) that are interconnected by a switching matrix. The switches are usually controlled by digital registers, which can be loaded by an external controller, thus allowing the FPAA to be configured to implement a number of different designs. This type of FPAA is advantageous because potential sampling artefacts are avoided, so anti-aliasing filters are not needed, relatively easy design processes can be used, and large signal bandwidths can be supported with predictable performance [30]. However, the switching networks introduce parasitic impedances into the signal path that limit the bandwidth and add noise to the system. Thus, most of the research effort has focused on minimizing the number of switches in the signal path, but this can severely limit the flexibility of the FPAA [33, 5, 34, and 35].

## IV.2. EVOLUTION

Since the 1990s lot of effort has been done to develop analogue architectures with a functional philosophy similar to the digital FPGAs one. This effort resulted in various techniques in some academic efforts that converge all into the development of more sophisticated FPAA circuits, and some commercial products. It is worth describing in brief some academic research works and some commercial products that appeared in the last two decades (Some of these commercial products were discontinued, and some others are still available).

### IV.2.1. ACADEMIC EVOLUTION

#### A. ELECTRONIC SYSTEMS DESIGN GROUP AT UNIVERSITY OF SOUTHAMPTON,

Where, continuous time FPAA architectures were developed. The group (active until 2008) presented in [36] the continuous-time Hierarchical Field Programmable Analogue Array (HFPAA). This system presents a Differential Difference Amplifier (DDA) as the CAB, and an example of mixed signal version of this circuit where dual voltage/current output mode is used.
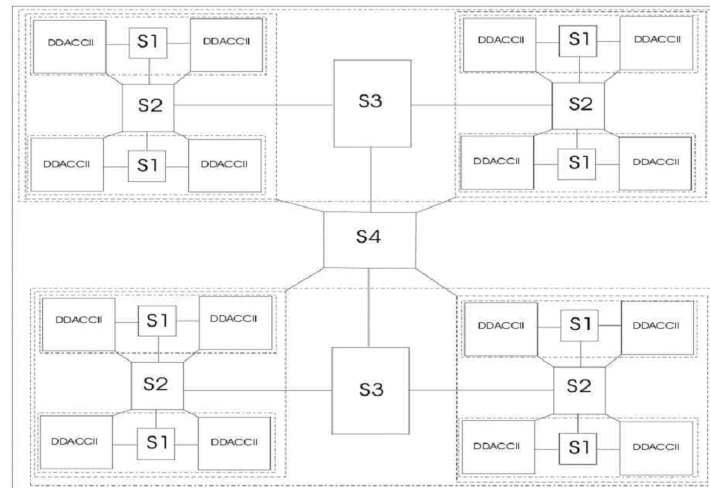


*Fig.II.7*: Hierarchical Field Programmable Analogue Array [37]

However, the proposed continuous time architecture uses hierarchical interconnection switches to achieve maximum routing capability between CABs and minimum number of routing resources.

## B. COOPERATIVE ANALOGUE AND DIGITAL SIGNAL PROCESSING (CADSP) AT GEORGIA TECHNOLOGY INSTITUTE,

Where a group of scientist continue the development of floating gate technique in FPAA [8, 38, and 39] architectures. By using floating gates as a switch for signal routing or even to reconfigure the function parameters, the group aims at very high-density field-programmable analogue arrays. Here, in this particular kind of architectures, several different CABs architectures can be implemented at once using this technique. For instance, in [40], two CABs were implemented, containing a mixture of fine-grained (MOSFETs and capacitors), medium-grained (OTAs), and coarse-grained (capacitively coupled current conveyors) computational blocks. Signals are routed using crossbars and switch-matrices using floating gate devices.
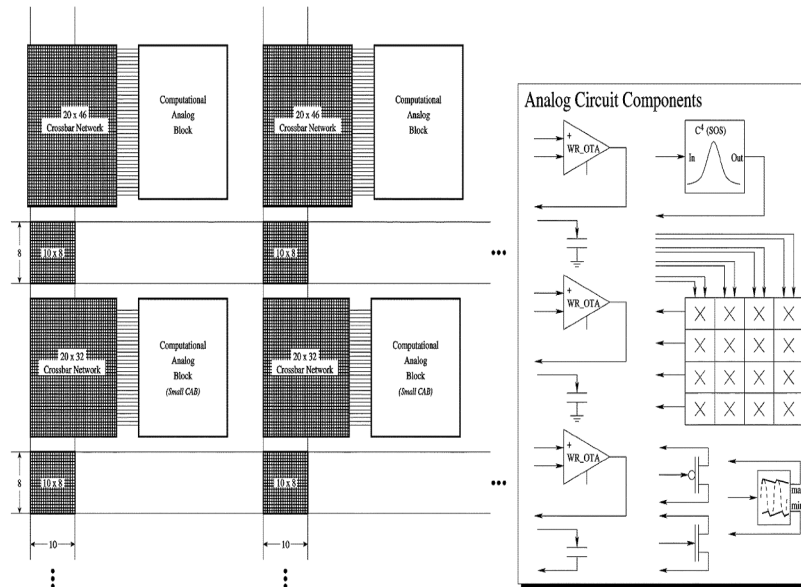


*Fig.II.8: Large scale FPAA as in [40]*

## C. NASA'S FIELD PROGRAMMABLE TRANSISTOR ARRAY (FPTA) OR SELF-CONFIGURABLE AND EVOLVABLE HARDWARE CIRCUITS

Here, a group works on adaptive techniques for the use in analogue processing is reported in [17]. Where objective were to develop a class of self-configurable and evolvable hardware, which adapts to its working environment to obtain optimal signal processing and provides fault tolerant functionality. In particular the group working was focused on Field Programmable Transistor Array (FPTA), where the CABs are fine-grained

components like MOSFETs. However, in the Evolutionary Oriented Reconfigurable Architecture (EORA) reported in [41], CABs were made of 8 transistors (4 PMOS and 4 NMOS), and 24 switches. Here, the CABs are divided into clusters, where each cluster presents CABs with different transistor sizes, and the routing is performed by switches and multiplexers. FPTA has also been the subject of other groups' activity like the work reported in [42], where the FPTA architecture is based on all-PMOS and all-NMOS CABs configurable in up to 75 different sizes in a checker-board pattern and routed using also switch-matrices and multiplexers. And also the designed called Self-Reconfigurable Analogue Array (SRAA) based on medium coarse granularity (OTA) reported in [43].
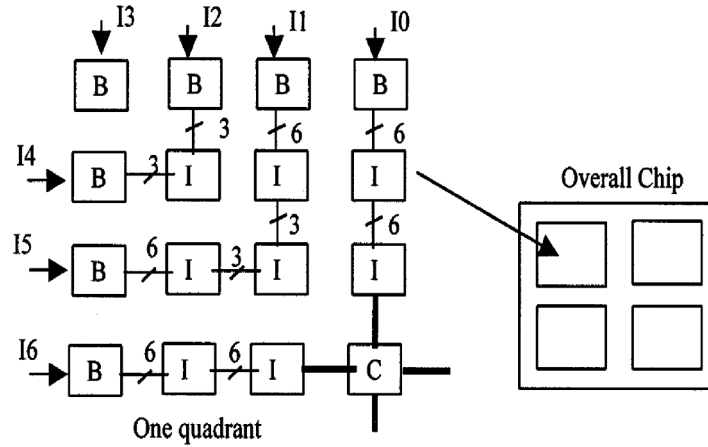


***Fig.II.9***: *Field Programmable Transistor Array (FPTA) presented in [17]*

## D. GM-C BASED FIELD PROGRAMMABLE ANALOGUE ARRAY

At the Department of Microelectronics at Ulm University, a group of searchers has developed a reconfigurable analogue array circuit architecture based on digitally configurable transconductors. These continuous-time CABs present a number (normally seven) of binary weighted sizes Gm-cells that can be turned on or off to perform the desired configuration. These cells are configured in a parallel mode to obtain different transconductances. In this architecture, the CABs are also used to routing the signals inside the system and, therefore, avoiding the use of switches in the signal path [44]. In [45] an alternative implementation has been reported, in which the new

architecture uses floating-gates to add current programmability and a 3-bit capacitor array.
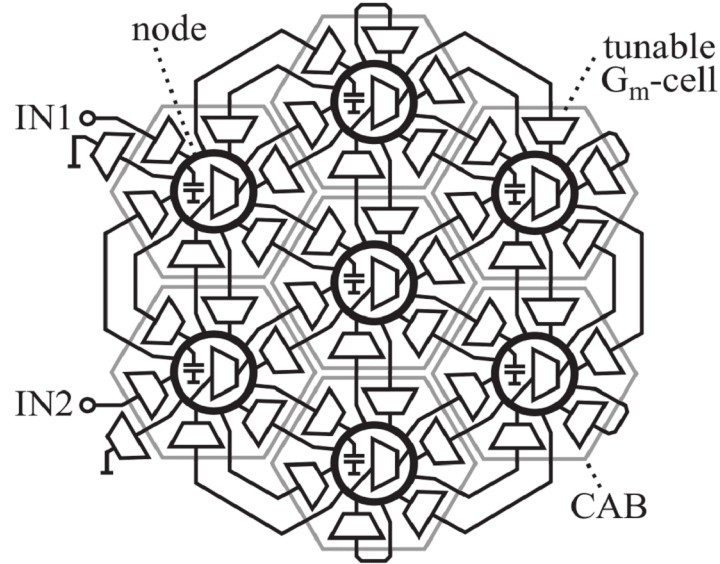


**Fig.II.10**: *The Gm-C based Field Programmable Analogue Array with floating gate transistors [45]*

## E. CELLULAR NEURAL NETWORKS (CNN) FPAA'S BASED ARCHITECTURES

In Robotics & Biosystems group at University of Berkeley California, a group of searcher has developed reconfigurable analogue array architecture based on Cellular Neural (or Non-linear) Networks (CNN). The Universal Machine version of this architecture (CNN-UM) is based on the concept of specific connectivity model and analogue circuit dynamic with continuous valued state variables [46]. Signals are routed through direct, local interactions within a finite radius, however further cells can be "virtually" connected due to dynamic propagation.
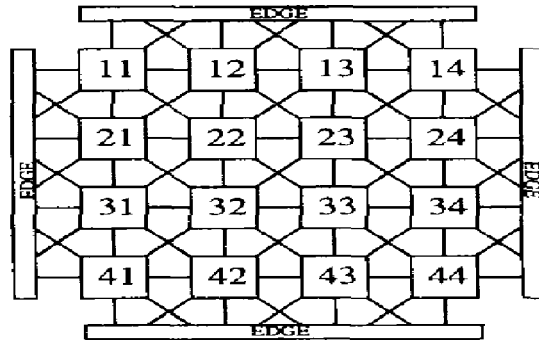


**Fig.II.11** : *Analogue programmable Cellular Neural Network (CNN) chip [47]*

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The CNN techniques and applications involved other groups and researchers resulting in the development of a particular architecture mainly used to model physical phenomena, neuromorphic control and different applications like visual processing [47].

## IV.2.2 COMMERCIAL EVOLUTION

### a. TOTALLY RECONFIGURABLE ANALOGUE CIRCUIT (TRAC)

TRAC represents actually one of the used technologies in performing analog programmable circuits, which has been introduced by the Fast Analogue Solutions branch of Zetex group about twenty years ago. This architecture operates in continuous mode and concern essentially a collection of operational amplifiers configured as one of a set of predefined functions to process analogue signals [48]. TRAC020LH [49] is one of those FPAA chips proposed by Zetex, it contain twenty CABs where each one can be configured to perform summation (of two signals), negation, logarithm compression, anti-log expansion, rectification, amplification, differentiation and. Further operations are possible combining them, like filtering.
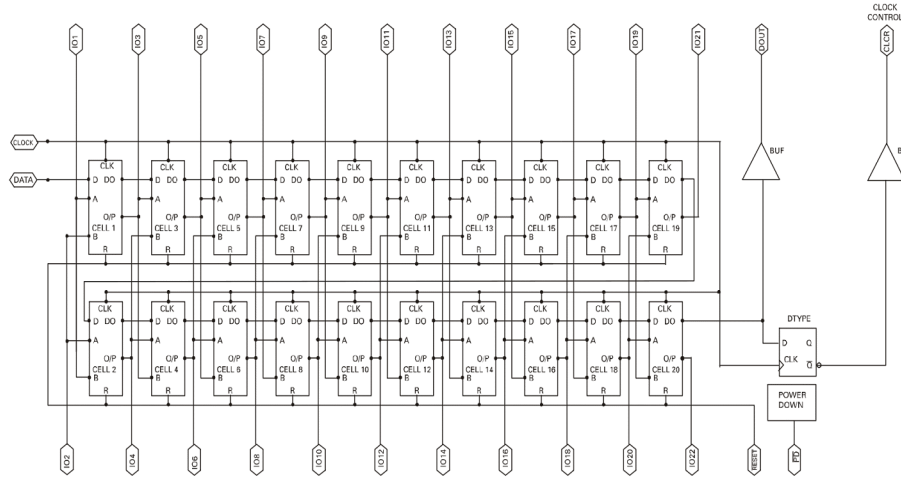


*Fig. II.12*: *The architecture of TRAC020LH FPAA from Zetex [49]*

### b. FIELD PROGRAMMABLE SYSTEM ON A CHIP (FIPSOC)

FIPSOC system From Sidsa, is a mixed mode programmable circuit originally designed for general front end and data acquisition purposes [50]. This type of circuit contains twelve differential amplifiers combined in four input channels, four comparators, one analogue multiplexer, ADC/DAC

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blocks and a digital micro-controller and memory [51]. The system is configured by the micro-controller or the internal logic using the ADC and DAC blocks. Signal routing is performed by the analogue multiplexer.
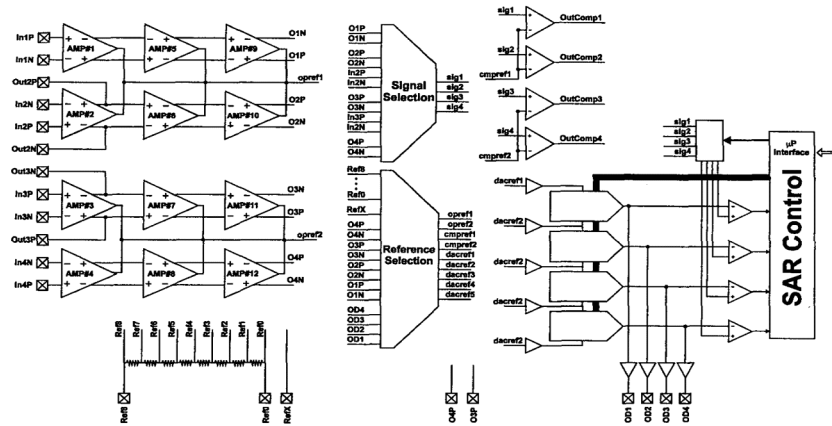


*Fig.II.13*: *FipSoc [51] from Sidsa*

## c. In-system programmable analogue circuit (ispPACR )

These circuits from Lattice Semiconductor Corporation are hierarchically built from basic cells called PACell grouped in functional modules (called PAC block) and using an Analogue Rooting Pool (ARP) to connect PACell and PACblocks inputs and outputs, PACs and the device pins [52].
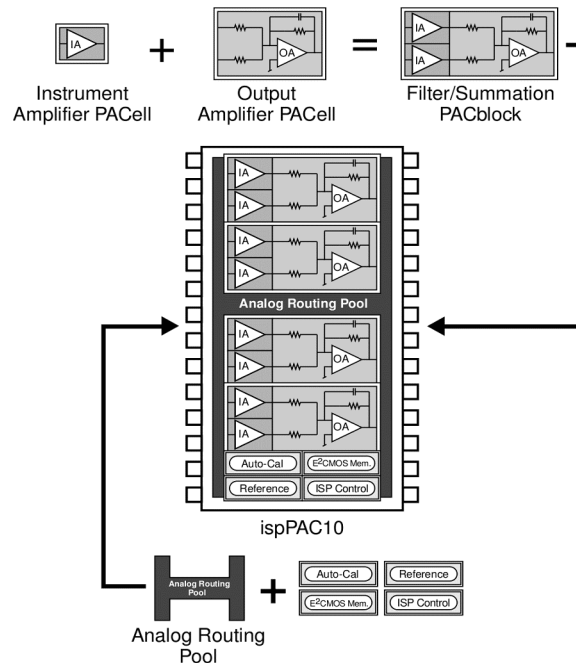


*Fig.II.14* : *ispPAC10 [52] from Lattice*

Each product in the family was designed to one specific function and each one has its own PACells [53]. For instance, the  PACells of ispPACR 10 , which  targeted to signal conditioning functions, like amplification and filtering,  consist of four PCA blocks containing amplifiers (instrumentation and summing amplifiers) and arrays of capacitors. Elements like comparators and polarity switches are added to the ispPAC10's PACells architecture to include non-linear processing in the second version of these chips which was called "ispPACR20". Finally, the version "IspPACR30's PACells include multiplying DACs, which make it a fully programmable mixed signal array (FPMA).

## D. MIXED-SIGNAL PROGRAMMABLE SYSTEM-ON-CHIP (PSOCR )

It is a family of FPAA architectures from Cypress Semiconductor which contain both digital and analogue programmable blocks, with supporting circuits, as SRAMs, clock generators and micro-controllers (M8, 8051 or ARM). Each block of PSoCR1 sub-family consists of one operational amplifier. Additional circuitry determines whether they will operate either in continuous-time or discrete time mode. Rather than providing universal connectivity and switch programming, each block presents multiplexers sourcing the amplifier inputs, resistor strings, capacitor terminals from its neighbour blocks outputs [54].
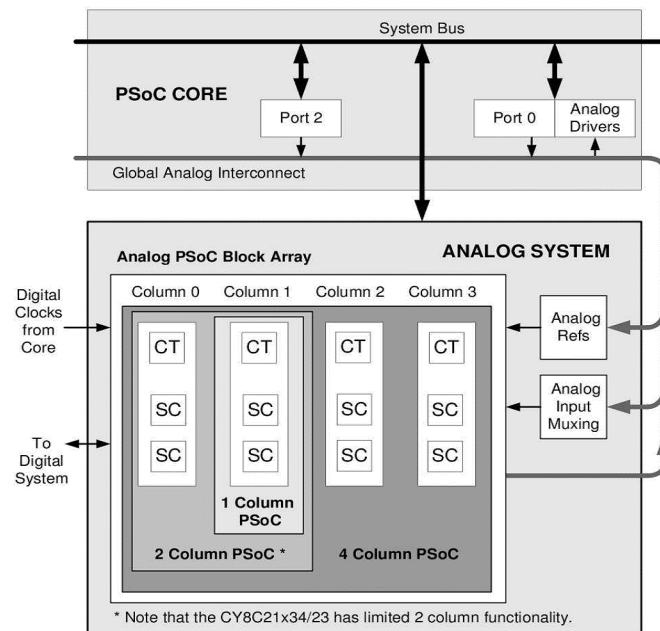


*Fig.II.15*: PSoC CY8C27x43 [54] from Cypress.

Block designs were optimized to support a few key functions such as a delta -sigma modulator, a gain amplifier, digital-to-analogue converter (DAC), or differencing amplifier [55].

### e. Cellular Visual Microprocessor (CVM)

This chip from AnaLogic Computers Ltd USA is a visual sensor and processor based on Cellular Neural Networks (CNN) technique. Where, the CAB is built with several different circuits like analogue multipliers, non-linear dynamic blocks, analogue memory, optical detection circuits and others. Each CAB is analogue connected with other eight adjacent CABs and digitally connected with column ADC and DAC. For instance, ACE16k1 is a 128x128 Focal-Plane Analogue Programmable Array Processor target to work with high speed and moderate accuracy (around 8bits) requirements [56].
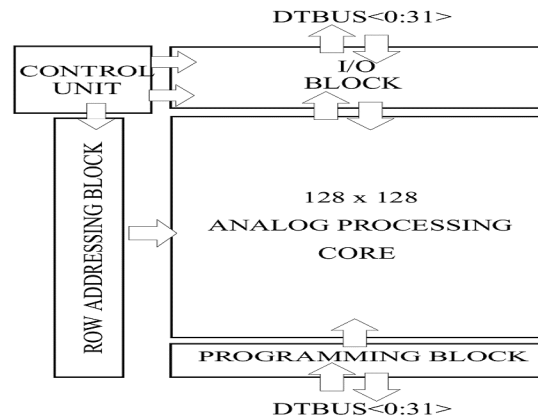


*Fig.II.16: ACE16k [56] from CNM-CSIC*

### f. Dynamically programmed Analogue Signal Processors (dpASP)

and Field Programmable Analogue Arrays (FPAA) from Anadigm the former Motorola's reconfigurable analogue group [57] designed new system consisting of a matrix of fully Configurable Analogue Blocks (CABs), surrounded by programmable interconnect resources and analogue inputs and output cells with active elements and supporting circuits. The first generation of these systems presented up to twenty CABs [58], but current products work with just four CABs [59] in order to present greater signal-to-noise ratio and bandwidth. Anadigm's products are based on switched-

capacitor circuit techniques. Therefore, the core of their CABs is one operational amplifier and a programmable bank of capacitors and they are surrounded by a fabric of programmable interconnect resources, such as band-gap circuits, clock generators and lookup tables. These CABs are routed inside and to external pins using local and global switch-matrices.
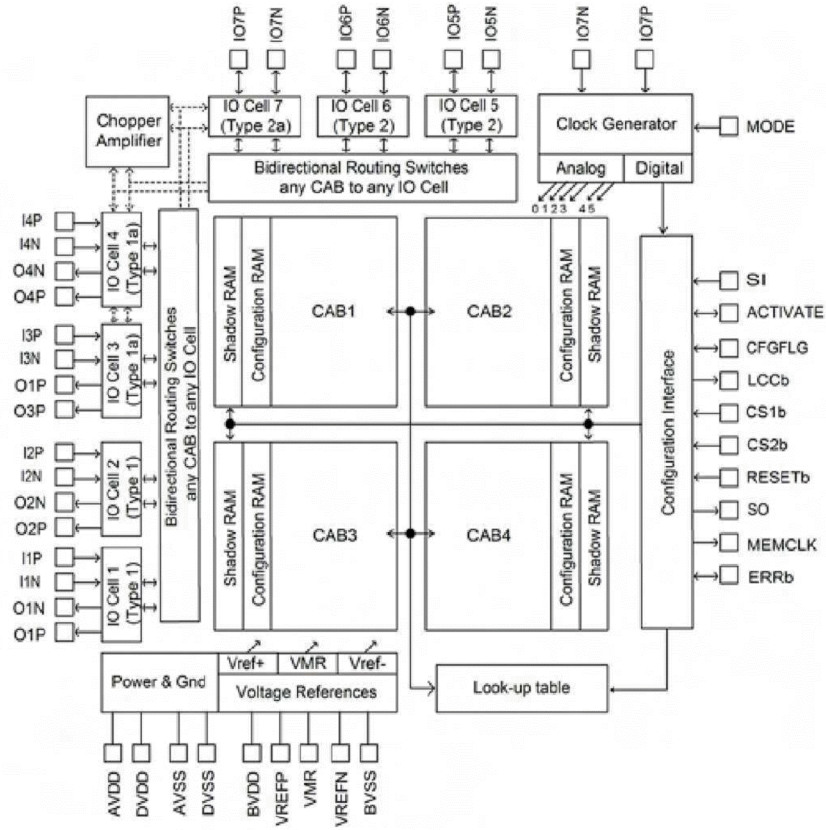


*Fig.II.17*: AN231E04 [59] from Anadigm

# V. Bibliography

[1] "Wireless Communication Circuits and Systems" by Yichuang Sun; SBN-10: 0852964439; ISBN-13: 978-0852964439; 2004.

[2] Sivilotti, M. A.: 'A dynamically configurable architecture for prototyping analog circuits'. Proceedings of Decennial Caltech Conference on *Advanced Research in VLSI*, Cambridge, MA, March 1988, pp. 237–58.

[3] Gaudet, V. C. and Gulak, P. G.: 'Implementation issues for high-bandwidth field-programmable analog arrays'. *Journal of Circuits, Systems and Computers*, 2000, 8 (5), pp. 541–58.

[4] Looby, C. A. and Lyden, C.: 'Op-amp based CMOS field-programmable analogue array'. *IEE Proceedings: Circuits, Devices and Systems*, April 2000, 147 (2),

[5] Lee, E. K. F. and Gulak, P. G.: 'A CMOS field programmable analog array', *IEEE Journal of Solid-State Circuits*, December 1991, 26 (12), pp. 1860–67.

[6] Lee, E. K. and Gulak, P. G.: 'A transconductor-based field-programmable analog array'. IEEE International Solid-State Circuits Conference Digest, San Francisco, CA, USA, February 1995, pp. 198–99.

[7] Wunderlich, R. B; Adil, F ; Hasler, P; "*Floating Gate-Based Field Programmable Mixed-Signal Array*"; IEEE Transactions on Very Large Scale Integration (VLSI) Systems; 19 September 2012; DOI: 10.1109/TVLSI.2012.2211049.

[8] Paul Hasler, Tyson S. Hall, and Christopher M. Twigg; " *Large-scale Field-Programmable Analog Arrays*"; The Neuromorphic Engineering, a publication of the INE-WEB.ORG;10.2417/1200503.0017; 2005.

[9] Ganesan, S.; Vemuri, R.;" *A Methodology for Rapid Prototyping of Analog Systems*", Computer Design, (ICCD '99) IEEE International Conference; Digital Object Identifier: 10.1109/ICCD.1999.808584; P:482 – 488. 1999.

[10] Mouna Karmani, Chiraz Khedhiri; belgacem Hamdi; " *Analog Integrated Circuit Design and Testing Using The Field Programmable Analog Array Technology*"; International journal of Advances in Engineering & technology; ISSN: 2231-1963, vol 1, Issue 4; pp. 1-9; 2011.

[11] TIAGO R. BALEN et al; "*Applying the Oscillation Test Strategy to FPAA's Configurable Analog Blocks*"; the *Fourth IEEE Latin American Test Workshop*, Natal, Brazil, Springer Science + Business Media, JOURNAL OF ELECTRONIC TESTING: Theory and Applications 21. 2005.

[12] Haydar KUTUK and Sung-MO (STEVE) KANG;" *A Switched Capacitor Approach to Field-Programmable Analog Array (FPAA) Design*", IEEE International symposium on circuits and systems ISCAS '96, Digital Object Identifier: 10.1109/ISCAS.1996.541896; Page(s): 41 - 44 vol.4. 1996.

[13] Anadigm Company, The AN10E40 field programmable analog array; www.**anadigm**.com.

[14] Laknaur, Amit and Wang, Haibo, "*A Methodology to Perform Online Self-Testing for Field-Programmable Analog Array Circuits*"; IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 54, NO. 5. OCTOBER 2005.

[15] Johns, D. A., K. W. Martin. 1997. Analog integrated circuit design. New York: John Wiley & Sons. ISBN 0-471-14448-7.

[16] P. Hasler, "Low-power programmable signal processing," in *Proceedings of the Fifth International Workshop on System-on-Chip for Real-Time Applications*, (Washington, DC, USA), pp. 413 – 418, IEEE Computer Society, 2005.

[17] A. Stoica, R. Zebulum, D. Keymeulen, R. Tawel, T. Daud, and A. Thakoor, "Reconfigurable VLSI architectures for evolvable hardware: from experimental field programmable transistor arrays to evolution-oriented chips," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 9, pp. 227–232, Feb. 2001.

[18] T. Hall and C. Twigg, "Field-programmable analog arrays enable mixed-signal prototyping of embedded systems," in *48th Midwest Symposium on Circuits and Systems, 2005*, vol. 1, pp. 83–86, 2005.

[19] D. D'Mello and P. Gulak, "Design Approaches to Field-Programmable Analog Integrated Circuits," *Analog Integrated Circuits Signal Processing;* vol. 17, pp. 7–34, 1998.

[20] R. T. Edwards, K. Strohbehn, S. E. Jaskulek, and R. Katz, "Analog module architecture for space-qualified field-programmable mixed-signal arrays," in *2nd annual Military and Aerospace Applications of Programmable Devices and Technologies Conference*, (Laurel, MD), 1999.

[21] E. K. F. Lee and W. L. Hui, "A novel switched-capacitor based field-programmable analog array architecture," *Analog Integrated Circuits and Signal Processing*, vol. 17, no. 1, pp. 35–50, 1998.

[22] T. Roska and L. O. Chua, "The CNN universal machine: an analogic array computer, *Transactions on Circuits and Systems II: Analog and Digital Signal Processing*, vol. 40, pp. 163–173, 1993.

[23] C. Santini, J. Amaral, M. Pacheco, M. Vellasco, and M. Szwarcman, "Evolutionary analog circuit design on a programmable analog multiplexer array," in *Proceedings of the IEEE International Conference on Field-Programmable Technology*, pp. 189–196, IEEE, 2002.

[24] M. A. Terry, J. Marcus, M. Farrell, V. Aggarwal, and U.-M. O'Reilly; "Generative robust analog circuit exploration". *Lecture notes in computer science*. vol. 3907; pp. 332–343, 2006.

[25] P. Dong, G. Bilbro, and M.-Y. Chow, "Implementation of Artificial Neural Network for Real Time Applications Using Field Programmable Analog Arrays," in *Proceedings of the IEEE International Joint Conference on Neural Network*, pp. 1518–1524, IEEE, 2006.

[26] S. Bridges, M. Figueroa, D. Hsu, and C. Diorio, "Field-Programmable Learning Arrays," *Neural Information Processing Systems*, vol. 15, pp. 1155–1162, 2003.

[27] C. Looby and C. Lyden, "Op-amp based CMOS field-programmable analogue array," *IEE Proceedings - Circuits, Devices and Systems*, vol. 147, no. 2, p. 93, 2000.

[28] K. Papathanasiou, T. Brandtner, and A. Hamilton, "Palmo: pulse-based signal processing for programmable analog VLSI," *IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing*, vol. 49, no. 6, pp. 379–389, 2002.

[29] R. Chawla, "Power-efficient analog systems to perform signal-processing using floating gate MOS device for portable applications". Phd; Georgia institute of Technology, 2004.

[30] Marsh, D., "Programmable analogue ICs challenge spice-and-breadboard designs," in EDN Europe, pp. 30-36, http://www.ednmag.com: Reed Business Information, Oct. 2001.

[31] Gulak, P. G., "Field-programmable analog arrays: past, present and future perspectives"; in IEEE Region 10 International Conference on Microelectronics and VLSI, pp. 123-126, Nov. 1995.

[32] Chang, S., Hayes-Gill, B., and Paul, C.,"Multi-function block for a switched current field programmable analog array,"; in 1996 Midwest Symposium on Circuits and Systems, Aug. 1996.

[33] Embabi, S., Quan, X., Oki, N., Manjrekar, A., and Sanchez-Sinencio, E., "A field programmable analog signal processing array"; in IEEE 39th Midwest Symposium on Circuits and Systems, vol. 1, pp. 151-154, Aug. 1996.

[34] Lee, K. and Gulak, P., "A CMOS field-programmable analog array"; in IEEE International Solid-State Conference Digest of Technical Papers, pp. 186-188, Feb. 1991.

[35] Pierzchala, E., Perkowski, M. A., Halen, P. V., and Schaumann, R., "Current-mode amplifier/integrator for a field-programmable analog array," in IEEE International Solid-State Conference Digest of Technical Papers, pp. 196-197, Feb. 1995.

[36] D. Varghese and J. Ross, "A continuous-time hierarchical field programmable analogue array," in *Proceedings of the IEEE Custom Integrated Circuits Conference*, pp. 190–193, IEEE, 2005.

[37] D. Varghese and J. N. Ross, "A continuous-time hierarchical field programmable analogue array for rapid prototyping and hierarchical approach to analogue systems design"; in *Proceedings of the 18th annual symposium on Integrated circuits and system design*, (New York, NY, USA), pp. 248–253, ACM, 2005.

[38] P. Hasler, B. A. Minch, and C. Diorio, "Adaptive circuits using pFET floating-gate devices," in *Proceedings 20th Anniversary Conference on Advanced Research in VLSI*, pp. 215–229, IEEE, Mar. 1999.

[39] M. R. Kucic, *"Analog computing arrays"*. Phd, Georgia Institute of Technology, 2004.

[40] T. Hall, C. Twigg, J. Gray, P. Hasler, and D. Anderson, "Large-scale field-programmable analog arrays for analog signal processing"; *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 52, no. 11, pp. 2298–2307, 2005.

[41] R. Zebulum, A. Stoica, and D. Keymeulen, "The design process of an volutionary oriented reconfigurable architecture," in *Proceedings of the 2000 Congress on Evolutionary Computation*, pp. 529–536, IEEE, 2000.

[42] J. Langeheine, J. Becker, S. Folling, K. Meier, and J. Schemmel, "A CMOS FPTA chip for intrinsic hardware evolution of analog electronic circuits," in *Proceedings 3rd NASA/- DoD Workshop on Evolvable Hardware*, pp. 172–175, IEEE Comput. Soc; 2001.

[43] A. Stoica, D. Keymeulen, R. Zebulum, M. Mojarradi, S. Katkoori, and T. Daud, "Adaptive and evolvable analog electronics for space applications," *Evolvable Systems: From Biology to Hardware*, vol. 4684, pp. 379–390, 2007.

[44] J. Becker and Y. Manoli, "A continuous-time field programmable analog array (FPAA) consisting of digitally reconfigurable Gm-cells," in

*Proceedings of the IEEE International Symposium on Circuits and Systems*, vol. 1, pp. I–1092–5, IEEE, May 2004.

[45] F. Henrici, J. Becker, S. Trendelenburg, D. DeDorigo, M. Ortmanns, and Y. Manoli, "A Field Programmable Analog Array using floating gates for high resolution tuning," in *Proceedings of the IEEE International Symposium on Circuits and Systems*, pp. 265–268, IEEE, May 2009.

[46] L. Chua and T. Roska; "The CNN paradigm,"; *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*; vol. 40, pp. 147–156, Mar. 1993.

[47] P. Kinget and M. S. J. Steyaert, "A programmable analog cellular neural network CMOS chip for high speed image processing," *IEEE Journal of Solid-State Circuits*, vol. 30, pp. 235–243, Mar. 1995.

[48] C. Evans-Pughe, "Programmable Analog: More Gain, Less Pain," 2001.

[49] Z. Plc., "Totally Re-Configurable Analog Circuit - TRAC020LH." 1999.

[50] E. Cant'o, J. Moreno, J. Cabestany, I. Lacadena, and J. Insenser, "Implementation of Virtual Circuits by Means of the FIPSOC Devices," *Field-Programmable Logic and Applications: The Roadmap to Reconfigurable Computing*, vol. 1896, pp. 87–95, 2000.

[51] J. Faura, I. Lacadena, A. Torralba, and J. Insenser, "Programmable analog hardware: a case study," in *IEEE International Conference on Electronics, Circuits and Systems*, vol. 1, pp. 297–300, IEEE, 1998.

[52] L. Semiconductor Corp., "ispPAC Overview," 2001.

[53] E. Ramsden, "The ispPAC family of reconfigurable analog circuits," in *Proceedings of the 3rd NASA/DoD Workshop on Evolvable Hardware*, (Long Beach, CA), pp. 176–181, IEEE Comput. Soc 2001.

[54] C. S. Corporation, "PSoC Programmable System-on-Chip Technical Reference Manual," 2010.

[55] M. Mar, B. Sullam, and E. Blom, "An architecture for a configurable mixed-signal device," *IEEE Journal of Solid-State Circuits*, vol. 38, pp. 565–568, Mar. 2003.

[56] G. Linan, R. Dominguez-Castro, S. Espejo, and A. Rodriguez-Vazquez, "ACE16K: An advanced focal-plane analog programmable array processor," in *Proceedings of the 27$^{th}$ European Solid-State Circuits Conference*, pp. 201–204, 2001.

[57] A. Bratt and I.Macbeth, "DPAD2Afield programmable analog array," *Analog Integrated Circuits and Signal Processing*, vol. 17, no. 1, pp. 67–89, 1998.

[58] M. Jankovec and M. Topic, "Analog circuit development system,"; in *The IEEE Region 8 EUROCON 2003. Computer as a Tool.*, vol. 1, pp. 125–129, IEEE, 2003.

[59] Anadigm Inc., "AN231E04 Datasheet Dynamically Reconfigurable dpASP," 2008.

[60] Quan, X., Embabi, S. H. K. and Sanchez-Sinencio, E; "A current-mode based field programmable analog array architecture for signal processing applications"; Proceedings of IEEE Custom Integrated Circuits Conference, Santa Clara, 1998, pp: 1261–1264.

# CHAPTER III:

# HEART AND ELECTROCARDIAM (ECG)

# I. INTRODUCTION

Biological signals, or biosignals, are space–time records of a biological event such as a beating heart or a contracting muscle. The electrical, chemical, and mechanical activity that occurs during these biological events produces signals that can be measured and analyzed. These biosignals contain a huge amount of information that can be used either to understand the fundamental physiological mechanisms of a specific biological event or system, as well as for medical diagnosis in several cases. The biosignals acquisition can be performed using a variety of methods, mainly based on relatively simple signal analysis techniques, which consist basically of a group of operations necessary to make the biosignal treatable, such as amplification, filtering, digitization, processing, and storage. These techniques are generally accomplished using either hardware or software solutions, starting from a simple electronics circuits to the complex computer programs. In addition to these common procedures, sophisticated digital processing methods are quite common and can significantly improve the quality of the retrieved data. These include signal averaging, wavelet analysis, and artificial intelligence techniques.

The bio-signals records on the human body can be distinguished according to their type which can be electrical or magnetic, and to the organ this signals come from (included also in their nomination) such as: electromyography EMG, electrocardiography ECG, electroencephalography EEG, electrogastrography EGG, electrohystography EHG, and electrooculography EOG, Magnetoencephalography MEG. Electrically speaking those signals are particular with their very weak range of amplitude (voltage level) and their very low frequency range (Tab.III.1).

**Tab.III.1:** *Some biophysiologic signals characteristics (Amplitude and range of Frequency).*

| SIGNAL | AMPLITUDE RANGE | FREQUENCY RANGE |
|--------|-----------------|-----------------|
| ECG | 1 mV to 5 mV | 0.05 Hz to 200 Hz |
| EMG | 50 μV to 10 mV | 0.01 Hz to 10 KHz |
| EEG | 2 μV to 200 μV | 0.5 Hz to 100 Hz |

In this work our attention is given to the electrocardiography recording ECG signal as a non invasive tool wildly used for the diagnosis of almost all the cardiac diseases, also used as a valuable source of information for lots of systems of heart malfunction's rehabilitation. The dealing with ECG signal in any kind of applications, a well understanding of the origin and the mechanism of propagation of the signal is recommended.

## II.THE HEART

The heart is one of the most important organs in the entire human body, located between the lungs in the middle of the chest, behind and slightly to the left of the breastbone (sternum). It is in reality nothing more than a pump, composed of muscle which pumps blood throughout the body, beating approximately 72 times per minute of our lives. The heart pumps the blood, which carries all the vital materials like oxygen, glucose, sodium, calcium and potassium…etc, which help our bodies to function and removes the waste products the body do not need.
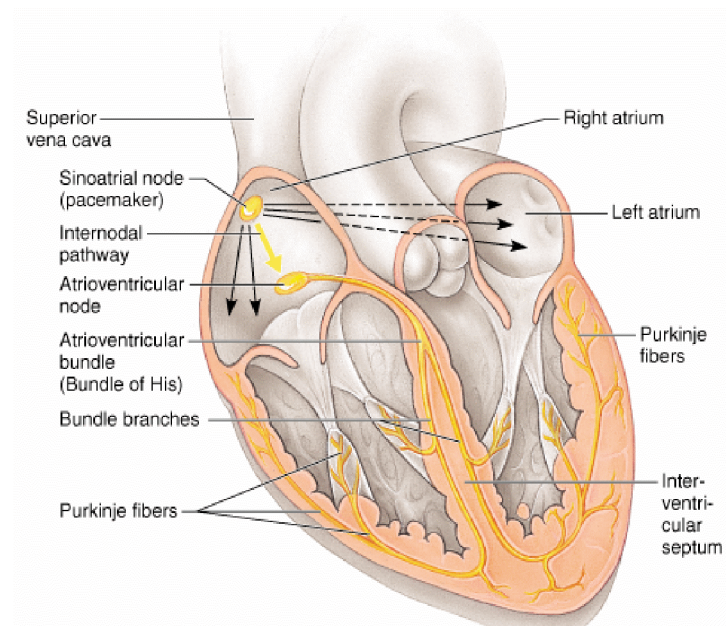


*Fig.III.1*: Heart anatomy

Anatomically speaking, the heart is composed of four chambers in total and several atrioventricular and sinoatrial node; the two upper chambers named the right and left atrium, while the lower two chambers are called the left and right ventricles (Fig.III.1).

In order to keep the ventricles electrically isolated from the atria, the last one is attached to the ventricles by fibrous, which is a non-conductive tissue. As mensioned previously the heart is nothing but a blood pump, formed by the pair of right atrium- right ventricle together to the circulate blood to the lungs. The mechanism known as the heart conducting system (Fig.III.2) consist mainly on the blood oxygen enrichment and then pumping to the body using the following process: Oxygen-poor blood is received through large veins called the superior and inferior vena cava and flows into the right atrium. The right atrium contracts and forces blood into the right ventricle, stretching the ventricle and maximizing its pumping (contraction) efficiency. The right ventricle then pumps the blood to the lungs where the blood is oxygenated. Similarly, the left atrium and the left ventricle together form a pump to circulate oxygen-enriched blood received from the lungs (via the pulmonary veins) to the rest of the body [1].
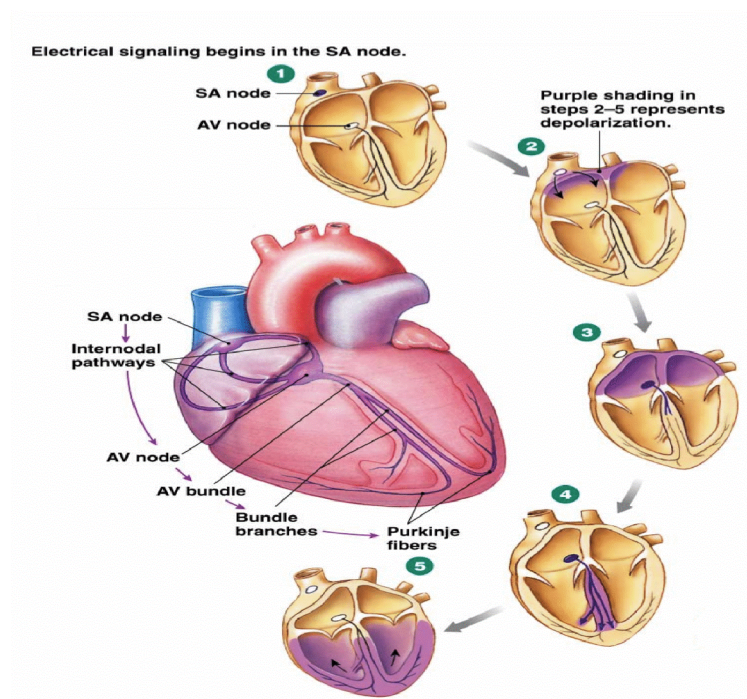


**Fig.III.2**: *The depolarization mechanism caused by the propagation of the stimulus in the heart conducting system.*

The heart mechanical pump is controlled with an electrical activity (Which consist of a regular electrical impulses generated spontaneously in heart Sino-atrial (S-A) node) that spread through the conduction system of the heart and initiate contraction of the myocardium. The propagation process of the electrical impulse through an excitable tissue is known as the

depolarization phenomena that can generate a strong ionic current (heart muscles depolarization) [2] as shown in Fig.III.3.
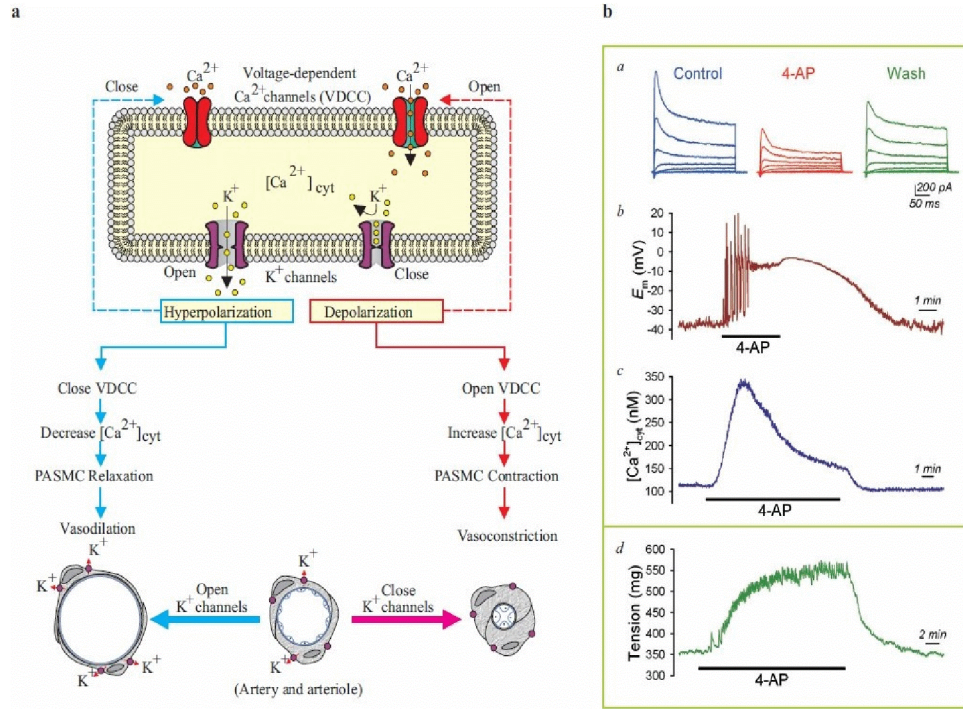


*Fig.III.3: The depolarization phenomena at the cells scale.*

The electro-chemistry behind the depolarization phenomena will be explained later on the next sections.

# III. THE ELECTROCARDIOGRAM ECG

From the previous sections, we know that the polarization phenomena (heart muscles depolarization) generates strong ionic current, which flows through the resistive body tissue, resulting in a voltage drop; that is large enough to be detected using electrodes based system attached to the skin. By definition, the records of such voltage drops caused by the ionic current flow generated from myocardial depolarization are called the Electrocardiogram (ECG) [3].

## III.1. THE ELECTROCARDIOGRAM (ECG) UTILITY

Since the day the Electrocardiogram was introduced into clinical practice more than 100 years ago by Einthoven [4], it was used as a diagnosis tool that reported the electrical activity of heart recorded by skin electrode, which can give information about the morphology and heart rate that

reflects the cardiac health of human heart beat [2]. It is a non-invasive technique, considering that the signal is measured on the surface of human body to be used for the identification of the heart diseases [6].

The recorded ECG waveform can give information about any cardiac decease. In fact, any disorder of heart rate or rhythm, or change in the morphological pattern, is an indication of cardiac arrhythmia, which could be detected by just analyzing the ECG record: amplitude and duration of the P-QRS-T wave (to be discussed in the next sections) forming the ECG contain useful information about the nature of disease afflicting the heart. Also the ECG signal provides the following information of a human heart [7]:

✓ Heart position and its relative chamber size.

✓ Impulse origin and propagation (Fig.III.4).

✓ Heart rhythm and conduction disturbances

✓ Extent and location of myocardial ischemia.

✓ Changes in electrolyte concentrations.

✓ Drug effects on the heart.
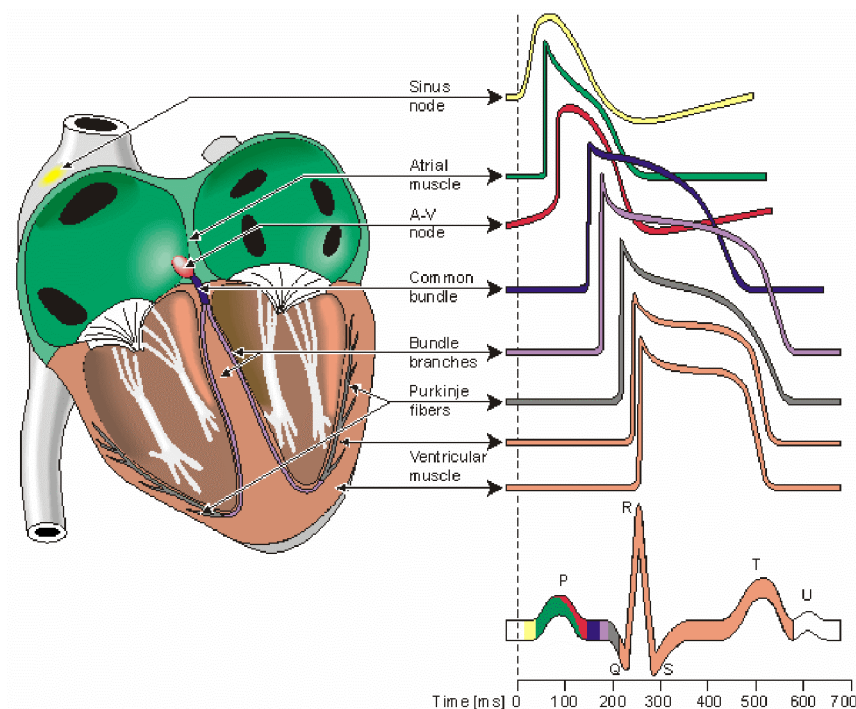


*Fig.III.4*: *Electrophysiology of the heart. The different waveforms for each of the specialized cells found in the heart are shown*

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## III. 2. THE ECG SIGNAL

The ECG is a differential signal recorded as a difference of electric potentials at two points inside the heart, on its surface, or on the human body surface. The ECG signal is a very reliable source of information, not only about the electrophysiological parameters of the heart, but it is also concerned by the heart function, anatomical aspect and mechanical properties [5]. To be able to well use the ECG signal in any kind of biomedical application, it is important to understand how this signal is generated through the heart anatomy and function. In the next section we will be discussing the electric activity of the heart starting from intracellular level to the heart itself.

### III.2.1. THE HEART ELECTRIC ACTIVITY

To understand the basis of the electric activity in the heart, we need to know how the signal is generated in the first place, then how it is propagating through the heart. From this point of view, the electric activity can be divided into two levels: the first one is the cardiac muscle cell electric activity, which explains the origin of the signal at the intracellular level. While the second one is related to the mechanism of current propagation through the heart muscle.

#### III.2.1.1. HEART ELECTRIC ACTIVITY AT THE INTRACELLULAR LEVEL

This type of electric activity takes place at the heart muscle cell. The depolarization mechanism is similar to the nerve cell one, based on the inflow of the sodium ions across the cell membrane. While the repolarisation results from the outflow of the potassium ions. The difference of the ions concentration between the inner and the outer side of the cell membrane, results in about 100 mV difference of potential between the two sides of the membrane with a duration of 300 ms, given rise to an electric current generated from the ions flow as shown in Fig.III.5 [8]. A late mechanical contraction is associated with electric activation of cardiac muscle cell, illustrated in Fig.III.6 [9]
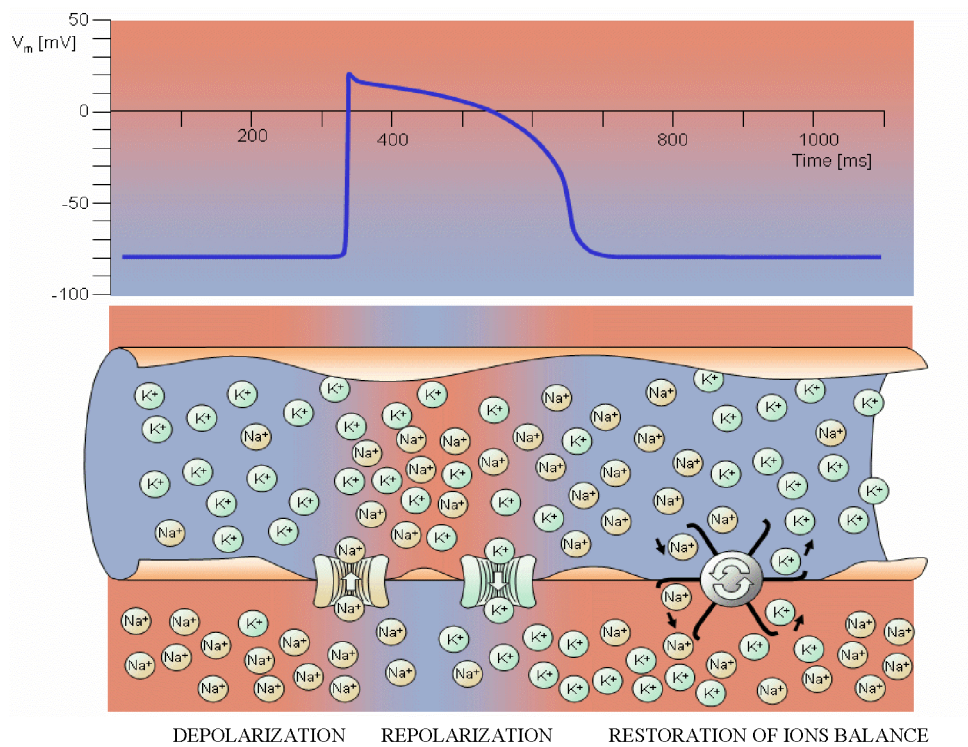
*Fig.III.5: Electrophysiology of the cardiac muscle cell.*

. An important distinction between cardiac muscle tissue and skeletal muscle is that in cardiac muscle, activation can propagate from one cell to another in any direction. As a result, the activation wave fronts are of rather complex shape.
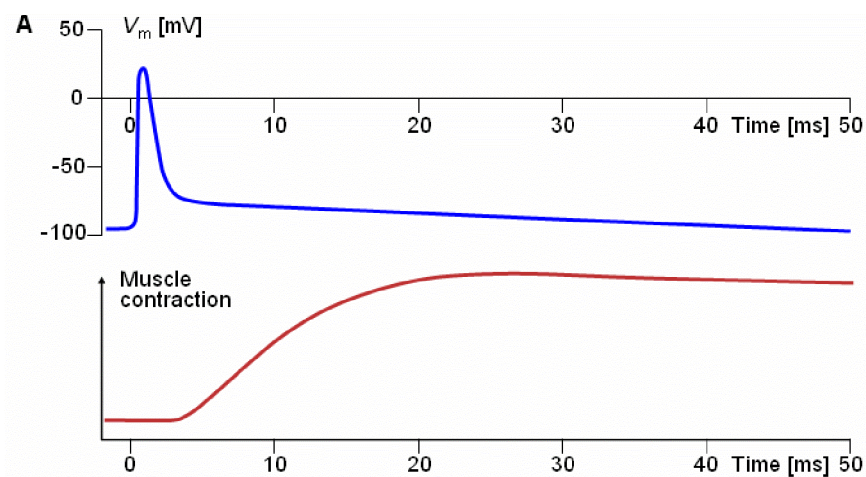


*Fig.III.6: Electric and mechanical activity in muscle cell, the upper curve shows the transmembrane voltage behaviour, whereas the lower one describes the mechanical contraction associated with it*

## III.2.1.2. Heart electric activity at the cardiac tissue level

In the previuos section the cardiac electric activity on the intracellular level was disscussed, this type of signal can be recorded using microelectrode, which is inserted inside a cardiac muscle cell, leading to an invasive diagnostic tool [4, 5]. The alternavive methode consist on recording extracellular electric behavior of the cardiac muscle tissue known as ECG, which can be performed by the measurments of the electric potential, generated by the electric activity of the heart, on the surface of the thorax.
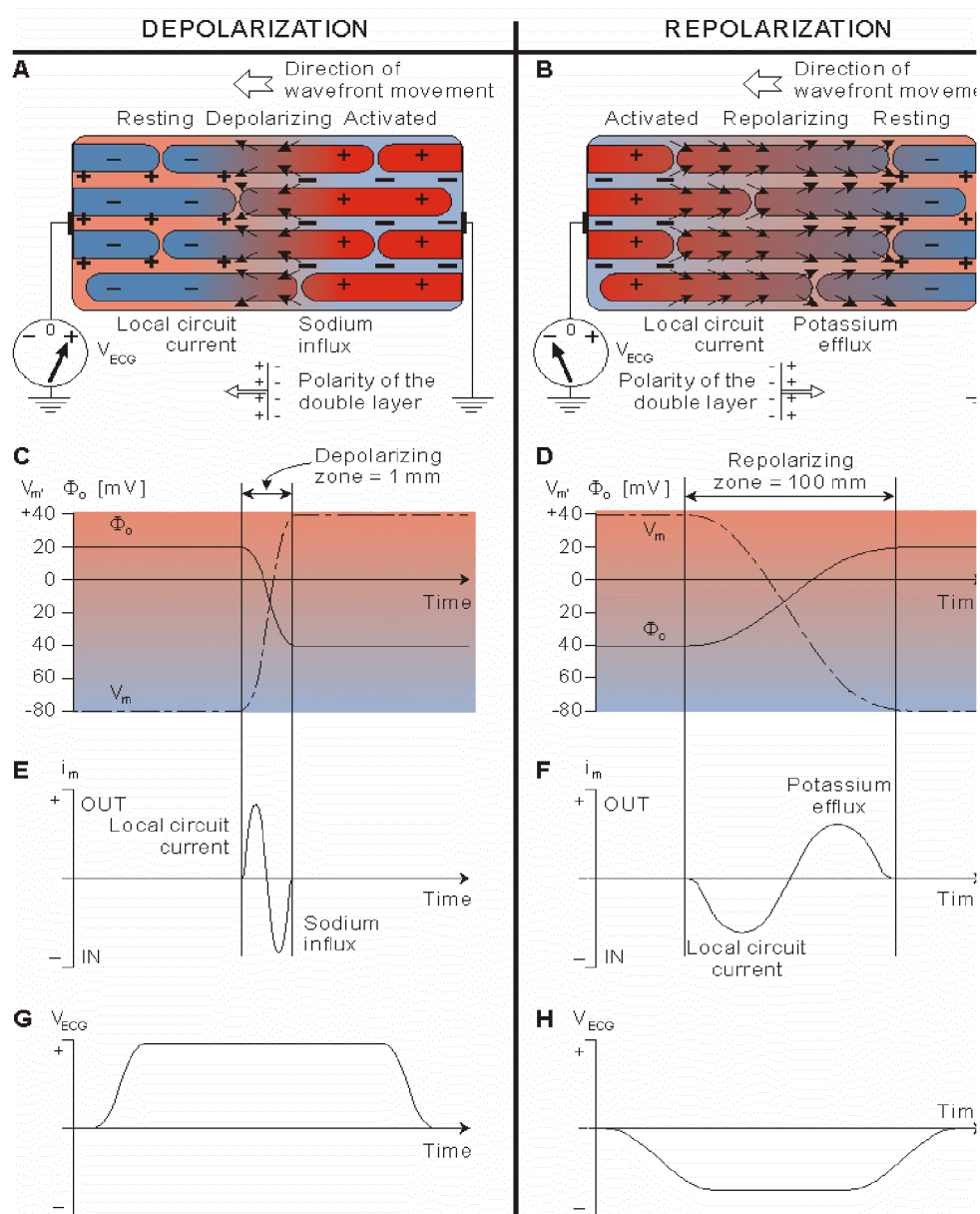


*Fig.III.7*: *The genesis of the electrocardiogram.*

The difference in the ion concentration between the intracellular and extracellular compartments creates an electrical potential difference across the membrane, which is essential to cell survival and function. The electrical potential difference between the outside and inside of a cell across the plasma membrane is called the membrane potential ($\Delta\Phi m$).

At rest, separation of charges and ionic concentrations across the membrane must be maintained for the resting potential to remain constant. At times, membrane potential changes in response to a change in the permeability of the membrane. This change in permeability occurs due to a stimulus, which may be in the form of a foreign chemical in the environment, a mechanical stimulus such as shear stress, or electrical pulses. For example, when the axon is stimulated by an electrical current, the Na+ ion channels at that node open and allow the diffusion of Na+ ions into the cell (Fig.III.7). This free diffusion of Na+ ions is driven by the greater concentration of Na+ ion outside the cell than inside [5]. Initially, diffusion is aided by the electric potential difference across the membrane. As the Na+ ion concentration inside the cell increases, the intracellular potential rises from −70 mV towards zero. A cell is said to be depolarized when the inside becomes more positive and it is said to be hyperpolarized when the inside becomes more negative. At the depolarized state, the Na+ ion diffusion is driven only by the concentration gradient, and continues despite the opposing electric potential difference. When the potential reaches a threshold level (+35 mV), the K+ ion channels open and permit the free diffusion of K+ ions out of the cell, thereby lowering and ultimately reversing the net charge inside the cell. When the K+ ion diffusion brings the intracellular potential back to its original value of resting potential (−70 mV), the diffusion channels close and the Na+ and K+ ion pumps turn on. Na+/K+ ion pumps are used to pump back Na+ and K+ ions in the opposite direction of their gradients to maintain the balance at the expense of energy [4, 5]. The Na+ ion pump transports Na+ ions out of the cell against the concentration gradient and the K pump transports K+ ions into the cell, also against the concentration gradient. When the original K+ ion and Na+ ion imbalances are restored the pumps stop transporting the ions. This entire process is similar in all excitable cells with the variation in the threshold levels.

## III. 2. 2. The Electrical Conduction System of the Heart

The conduction system of the heart is shown in Fig.III.8.The sino-atrial node (S-A) has the highest rate of spontaneous depolarization and acts as the primary pacemaker. At normal condition, the S-A node generates impulses that stimulate the atria to contract [5]. This node is located in the superior wall of the right atrium, close to the opening of the superior vena cava. Other elements of the conduction system include the atrio-ventricular node (A-V), located between the atria and the ventricles, in the lower atrial septum adjacent to the annulus of the mitral valve, and the bundle of His. The beginning of the atria contraction and the time of propagation of the stimulus till the A-V node is represented by the P wave on the ECG record. The bundle of His divides into a right and left branch at the level of membranous parts of the inter-ventricular septum. The left branch is further branched into an anterior and posterior bundle. The Purkinje fibers are the final component of the conduction system, which are intertwined with muscle fibers and the papillary muscles [5]. Their task is to conduct the wave fronts directly to the two ventricles so that they contract simultaneously, representing by that the QRS complex on the ECG record. And the T wave represents the re-polarization of the contracted ventricles to go back to their rest stat.
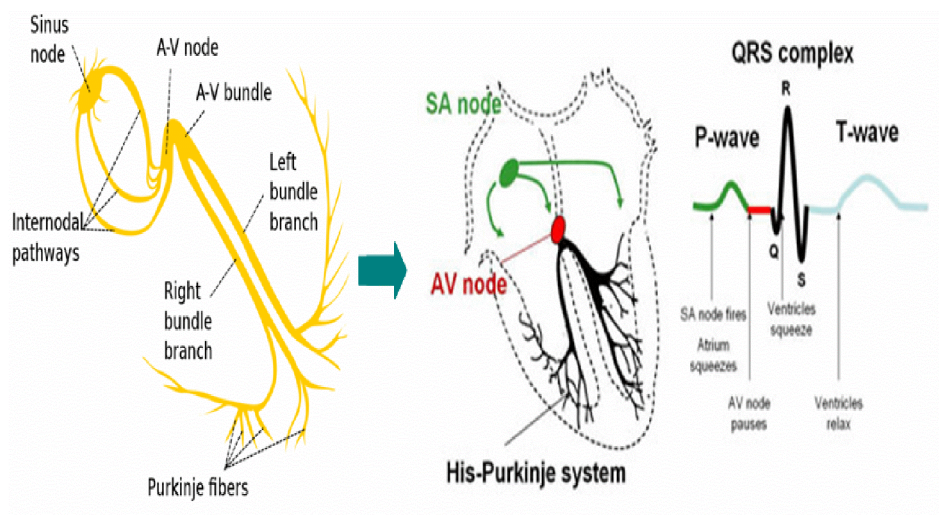


***Fig.III.8***: *The electrical conduction system of the heart*

## III. 3. The ECG measurements

The ECG signal is recorded using 12 leads connected to a recording system. Each one of those leas consist of a pair of electrodes (+ve & -ve) placed on the body in designated anatomical locations [7]; in order to record the potential difference between two points (+ve & -ve poles) knows as Bipolar leads, or to record the electrical potential at a particular point by means of a single exploring electrode Fig.III.9 show the distribution of the main leads on the ECG record.
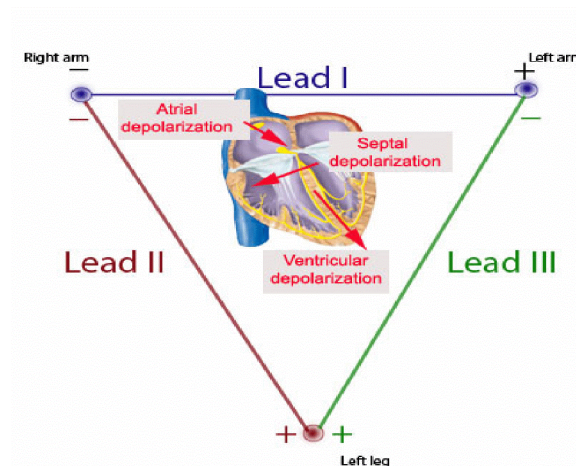


*Fig.III.9: The distribution of the main leads on the ECG record.*

Leads I, II and III are commonly referred to bipolar leads as they use only two electrodes to derive a view. One electrode acts as the positive electrode while the other as the negative electrode:

Lead I: records potentials between the left and right arm,

Lead II: between the right arm and left leg, and

Lead III: those between the left arm and left leg

## III. 4. ECG Waves and Time Intervals

Detection of the different elements of an ECG trace is the basis of some of the ECG recognition methods; therefore, in this section these elements and their temporal and frequency characteristics are briefly discussed.
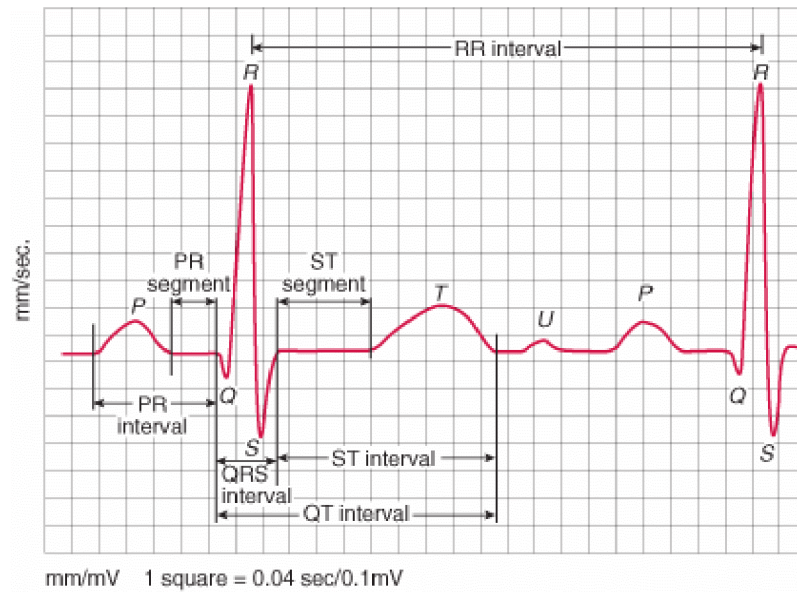
**Fig.III.10:** *Schematic representation of normal ECG waveform.*

The amplitude of a wave is measured with reference to the ECG baseline level and the duration of a wave is defined by two time instants at which the wave either deviates significantly from the baseline or crosses it. However, since there is no universal method to determine the onset and end of these elements [12], it is sometimes problematic to exactly localize the boundaries between the waves of an ECG trace. But, thanks to lot of statistical studies the normal limits of these parameters amplitude and duration were established for more comfortable ECG interpretation[4, 5 and12] (shown in Tab.III.2).

**Tab.III.2:** *Range of amplitude and time duration of normal ECG parameters.*

| ECG FEATURES | AMPLITUDE (mV) | TIME DURATION (ms) |
|---|---|---|
| P WAVE | 0.1-0.2 | 60-80 |
| PR SEGMENT | - | 50-120 |
| PR INTERVAL | - | 120-200 |
| QRS COMPLEX | 3-5 | 80-110 |
| ST SEGMENT | - | 100-120 |
| T WAVE | 0.1-0.3 | 120-160 |
| ST INTERVAL | - | 320 |
| RR INTERVAL | - | (0.6-1.2) s |

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## III. 4.1. P WAVE

During normal atrial depolarization, the main electrical vector is directed from the SA node towards the AV node, and spreads from the right atrium to the left atrium [4, 5, and 12]. This turns into the P wave on the ECG, which is upright in II, III, and a VF (since the general electrical activity is going toward the positive electrode in those leads), and inverted in a VR (since it is going away from the positive electrode for that lead). This wave has a smooth, mono-phasic morphology that reflects the sequential depolarization of the right and left atria. In most leads, the P wave has positive polarity with amplitude that is normally less than 300 μV and duration less than 120 ms. The spectral characteristic of a normal P wave is usually considered to be low-frequency, below 10−15Hz. However, noise-reduction techniques have helped to demonstrate the higher frequency components of the P wave that are useful if considered with the QRS complexes for predicting the occurrence of certain arrhythmias of particular arterial origin[13]:

• The shape and duration of the P waves may indicate atrial enlargement. The PR interval is measured from the beginning of the P wave to the beginning of the QRS complex. It is usually 120 to 200 ms long. On an ECG tracing, this corresponds to 3 to 5 small boxes

• A PR interval of over 200 ms may indicate a first degree heart block

• A short PR interval may indicate a pre-excitation syndrome via an accessory pathway that leads to early activation of the ventricles, such as seen in Wolff-Parkinson White syndrome

• A variable PR interval may indicate other types of heart block.

• PR segment depression may indicate atrial injury or pericarditis.

• Variable morphologies of P waves in a single ECG lead are suggestive of an ectopic pacemaker rhythm such as wandering pacemaker or multifocal atrial tachycardia.

### III.4.2 QRS COMPLEX

The QRS complex is a structure on the ECG that corresponds to the depolarization of the ventricles. Because the ventricles contain more muscle mass than the atria, the QRS complex is larger than the P wave. In addition, because the His/Purkinje system coordinates the depolarization of the ventricles, the QRS complex tends to look "spiked" rather than rounded due to the increase in conduction velocity [4, 5, 12]. A normal QRS complex is 0.06 to 0.10 sec (60 to 100 ms) in duration. Not every QRS complex contains a Q wave, an R wave, and an S wave. By convention, any combination of these waves can be referred to as a QRS complex. However, correct interpretation of difficult ECGs requires exact labeling of the various waves. Some authors use lowercase and capital letters, depending on the relative size of each wave. For example, an Rs complex would be positively deflected, while a RS complex would be negatively deflected. If both complexes were labeled RS, it would be impossible to appreciate this distinction without viewing the actual ECG. The duration, amplitude, and morphology of the QRS complex is useful in diagnosing cardiac arrhythmias, conduction abnormalities, ventricular hypertrophy, myocardial infarction, electrolyte derangements, and other disease states. Q waves can be normal (physiological) or pathological. Normal Q waves, when present, represent depolarization of the inter-ventricular septum. For this reason, they are referred to as septal Q waves, and can be appreciated in the lateral leads I, a VL, V5 and V6.Q waves greater than 1/3 the height of the R wave, greater than 0.04 sec (40 ms) in duration, or in the right precordial leads are considered to be abnormal, and may represent myocardial infarction.

### III.4.3 ST SEGMENT

The ST segment connects the QRS complex and the T wave and has duration of 0.08 to 0.12 sec (80 to 120 ms). It starts at the J point (junction between the QRS complex and ST segment) and ends at the beginning of the T wave. However, since it is usually difficult to determine exactly where the ST segment ends and the T wave begins, the relationship between the ST segment and T wave should be examined together [4, 5, 12]. The typical ST segment duration is usually around 0.08 sec (80 ms). It should be essentially level with the PR and TP segment. The normal ST segment has a

slight upward concavity. Flat, down sloping or depressed ST segments may indicate coronary ischemia. ST segment elevation may indicate myocardial infarction. An elevation of >1 mm and longer than 80 milliseconds following the J-point, this measure has a false positive rate of 15-20% (which is slightly higher in women than men) and a false negative rate of 20-30%.

### III.4.4 T WAVE

The T wave represents the repolarization (or recovery) of the ventricles. The interval from the beginning of the QRS complex to the apex of the T wave is referred to as the absolute refractory period. The last half of the T wave is referred to as the relative refractory period (or vulnerable period).In most leads, the T wave is positive. However, a negative T wave is normal in lead aVR. Lead V1 may have a positive, negative, or biphasic T wave. In addition, it is not uncommon to have an isolated negative T wave in lead III, a VL, or a VF. Inverted (or negative) T waves can be a sign of coronary ischemia, Wellens' syndrome, left ventricular hypertrophy, or CNS disorder. Tall or "tented" symmetrical T waves may indicate hyperkalemia. Flat T waves may indicate coronary ischemia or hypokalemia. The earliest electrocardiographic finding of acute myocardial infarction is sometimes the hyperacute T wave, which can be distinguished from hyperkalemia by the broad base and slight asymmetry [4, 5, and 12]. When a conduction abnormality (e.g., bundle branch block, paced rhythm) is present, the T wave should be deflected opposite the terminal deflection of the QRS complex. This is known as appropriate T wave discordance.

### III.4.5 QT INTERVAL

The QT interval is measured from the beginning of the QRS complex to the end of the T wave. A normal QT interval is usually about 0.40 seconds. The QT interval as well as the corrected QT interval is important in the diagnosis of long QT syndrome and short QT syndrome. The QT interval varies based on the heart rate, and various correction factors have been developed to correct the QT interval for the heart rate [4, 5, 12, and 13]. The most commonly used method for correcting the QTc interval for rate is the one formulated by Bazett and published in 1920. Bazett's formula is:

$$QTc = \frac{QT}{\sqrt{RR}}$$

Where QTc is the QT interval corrected for rate, and RR is the interval from the onset of one QRS complex to the onset of the next QRS complex, measured in seconds. However, this formula tends to be inaccurate, and over-corrects at high heart rates and under-corrects at low heart rates.

### III. 4. 6. U WAVE

The U wave is not always seen. It is typically small, and, by definition, follows the T wave. U waves are thought to represent repolarization of the papillary muscles or Purkinje fibers [4, 5, and 12]. Prominent U waves are most often seen in hypokalemia, but may be present in hypercalcemia, thyrotoxicosis, or exposure to digitalis, epinephrine, and Class 1A and 3 antiarrhythmics, as well as in congenital long QT syndrome and in the setting of intracranial hemorrhagic. An inverted U wave may represent myocardial ischemia or left ventricular volume overload.

### III. 5. NOISE AND ARTEFACTS

Raw ECG data contain some noise and artefact components that alter the expression of the ECG trace from the ideal structure described previously and render the clinical interpretation inaccurate and misleading; consequently, a pre-processing step for improving the signal quality is a necessity. It is therefore important to be familiar with the most common types of noise and artifacts in the ECG and address a method which can compensate for their presence before proceeding to the feature extraction step. Below follows some of the most common non-cardiac noise sources the first three of which are of technical origin whereas the fourth is of physiological origin [12].

### III. 5. 1. POWER LINE INTERFERENCE

Power line interference (50/60 Hz): is high frequency noise caused by interferences from nearby devices as a result of improper grounding of the ECG equipment (Fig.III.11). Indicated as an impulse or spike at 60 Hz/50 Hz harmonics, and will appear as additional spikes at integral multiples of the fundamental frequency. Its frequency content is 60 Hz/50 Hz and its harmonics, amplitude is up to 50 percent of peak to peak ECG signal

amplitude [10]. A 50/60 Hz notch filter can be used remove the power line interferences [11].
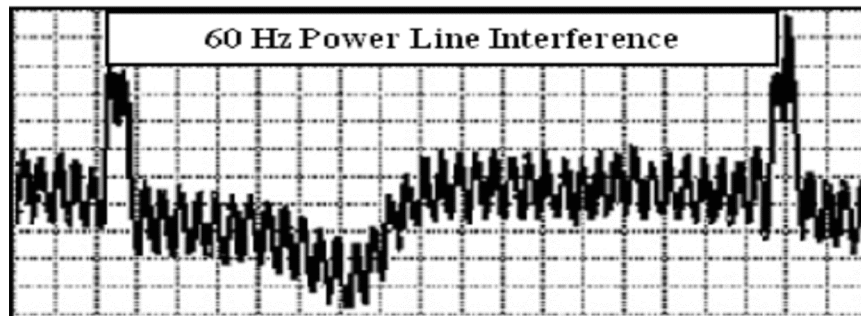


*Fig.III.11:* 60 Hz Power line interference.

## III. 5. 2. BASELINE WANDER

Is extraneous noise in the ECG trace that may be caused from a variety of noise sources including perspiration, respiration, body movements, and poor electrode contact.
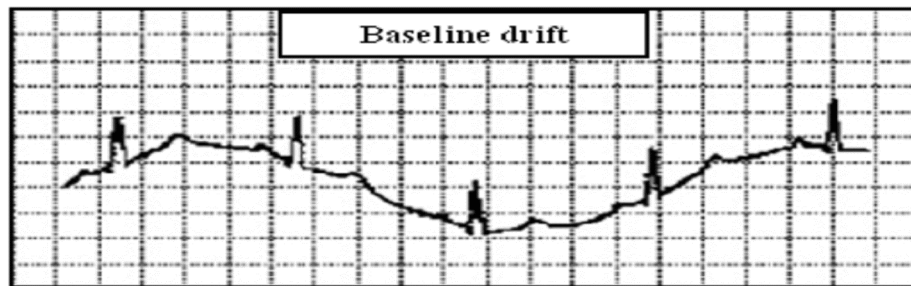


*Fig.III.12:* Baseline drifts in ECG signal

The magnitude of this wander may exceed the amplitude of the QRS complex by several times, but its spectral content is usually confined to an interval below 1Hz (*Fig.III.12*). Its frequency range generally below 0.5 Hz. To remove baseline drift a high pass filter with cut-off frequency 0.5 Hz is used [11].

## III. 5. 3. ELECTRODE MOTION ARTEFACTS

Are manifested as large-amplitude waveforms which are mainly caused by skin stretching which alters the impedance of the skin around the electrode (Fig.III.13). The peak amplitude of this artifact is 500 % of Peak to Peak ECG amplitude and its duration is about 100 – 500 ms [10].
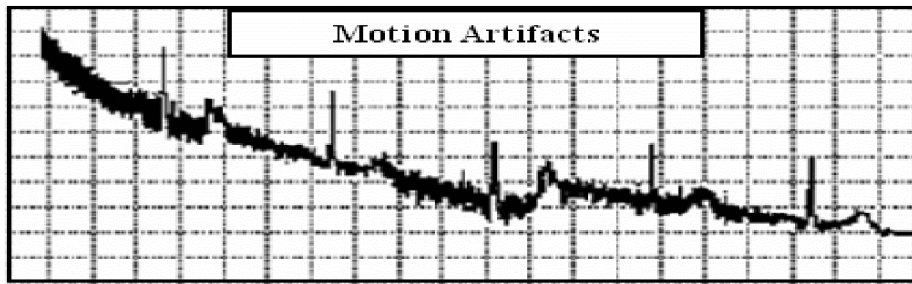
*Fig.III.13*: *Motion artifacts in ECG signal.*

They are more problematic to combat since their spectral content is mainly in the range of 1Hz − 10Hz that considerably overlaps within the PQRST complex an adaptive filter can be used to remove the interference of motion artifacts.

## III. 5. 4. ELECTROMYOGRAPHIC NOISE (EMG NOISE)

Is mainly caused either by the electrical activity of skeletal muscles during periods of contraction, or due to a sudden body movement (Fig.III.14). While the frequency component of EMG considerably overlaps with that of the QRS complex, it also extends into higher frequencies.
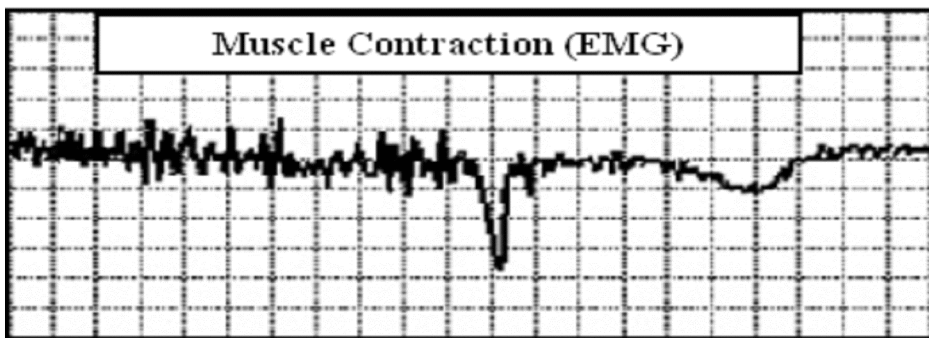


*Fig.III.14* : *Electromyographic noise (EMG noise)*

As a result, processing the ECG trace to remove these noise effects naturally results in introducing some distortion to the signal. Its frequency content is dc to 10 KHz and duration is 50 ms [10]. To remove the interference of due to EMG a morphological filter of a unit square-wave structuring (best width is 0.07 s) is used [11].

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# IV. Bibliography

[1] P.de Chazal, M.O. Duyer, and R.B. Reilly, "Automatic classification of heartbeat using ECG morphology and heart beat interval features," IEEE Trans. Biomed. Eng. vol. 51, pp. 1196-1206, 2004.

[2] J. Pan, W. J. Tompkins, "A real time QRS detection algorithm," IEEE Trans. Biomed. Eng., vol. 32, pp. 230– 236, 1985.

[3] W. Jiang and S. G. Kong, "Block-based neural networks for personalized ECG signal classification," IEEE Trans. Neural Netw., vol. 18, no. 6, pp. 1750–1761, Nov. 2007.

[4] A. Bayés de Luna, "Basic Electrocardiography: NORMAL AND ABNORMAL ECG PATTERNS", 2007, ISBN: 978-1-4051-7570-8.

[5] Adam Gacek, Witold Pedrycz; " ECG Signal Processing, Classification and Interpretation"; Springer London Dordrecht Heidelberg New York publication; ISBN 978-0-85729-867-6; e-ISBN 978-0-85729-868-3; DOI 10.1007/978-0-85729-868-3. 2011.

[6] W. Jiang and S. G. Kong, "Block-based neural networks for personalized ECG signal classification," IEEE Trans. Neural Netw., vol. 18, no. 6, pp. 1750–1761, Nov. 2007.

[7] S. Osowski, T. H. Linh, and T. Markiewicz, "Support vector machinebased expert system for reliable heart beat recognition," IEEE Trans. Biomed. Eng., vol. 51, no. 4, pp. 582–589, Apr. 2004.

[8] Netter FH (1971): Heart, Vol. 5, 293 pp. The Ciba Collection of Medical Illustrations, Ciba Pharmaceutical Company, Summit, N.J.

[9]. Ruch TC, Patton HD (eds.) (1982): Physiology and Biophysics, 20th ed., 1242 pp. W. B. Saunders, Philadelphia.

[10] American National Standard for Ambulatory Electrocardiographs, publication ANSI/AAMI EC38-1994, Association for the Advancement of Medical Instrumentation, 1994.

[11] Simon Haykin, Neural networks a comprehensive foundation, Pearson Prentice Hall, pp.178-330.

[12] L. Srnmo, P. Laguna, Bioelectrical Signal Processing in Cardiac and Neurological Applications,Elsevier Inc, 2005.

[13] http://en.wikipedia.org/wiki/Electrical_conduction_system_of_the_heart

# CHAPTER IV:

# EXPERIMENTAL RESULTS

# I. INTRODUCTION

In this part of the thesis we will present in details the different aspects of our experimental study carried out to assess the immunity of the FPAA circuit, configured as conditioning signal block for ECG signal. These details concern a description of the FPAA configuration, the nominal conditions measurements of the target parameters, the description of the first test differential approach based methodology followed by the different obtained measurement results and their evaluation, then, the description of the second test methodology based on the association of frequency analysis and time analysis of the ECG signal, followed by the different obtained test measurements with the evaluation of each part results. And finally we stress on some remarks derived from the test results obtained during the different experimental steps with some useful recommendations.

## II. DESCRIPTION OF A TYPICAL ANALOGUE ACQUISITION SYSTEM FOR BIOMEDICAL APPLICATION

A typical acquisition analogue system suitable for such bio-physiological signals as the ECG usually includes tow principal stages as shown in Fig.IV.1:

1) An amplification stage characterized by:

   ✓ High voltage gain (up to 1000 or greater),

   ✓ Common mode rejection ratio (CMRR) to guarantee the attenuation of the common mode noise.

   ✓ High input impedance (up to some Mega-Ohm) to avoid the attenuation of the ECG signal at the input and to provide a good isolation of the patient.

2) A composed filtering stage to select the signal frequency band of interest [0.05 Hz to 150 Hz] composed of:

   ✓ High pass filter to eliminate the DC component and the low frequency noise, characterized by the cut-off frequency $f_c= 0.05$ Hz.

   ✓ Notches filter to suppress the power line noise.

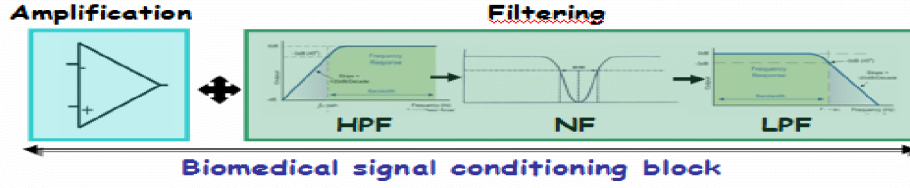✓ Low pass filter to eliminate the high frequency noise, characterized by the cut-off frequency fc = 150 Hz.



*Fig.IV.1*: *The typical architecture of signal conditioning block.*

In our research, to be able to implement this typical architecture on the FPAA circuit we are using AN221E04 circuit which is mounted on a starter kit, provided by Anadigm, we inspired from the work of D.P. Morales et al in [1]. Following the details given in the paper, we built the architecture of the front-end element to condition the ECG signal, by using the different available CAMs available in the predefined library provided by Anadigm. This library is actually integrated with the tool provided by the same company called AnadigmDesigner2 [2] that we use for design and configuration of the FPAA circuit.

## III. FPAA Configuration

Once the architecture to be implemented into the FPAA circuit is designed and simulated for the well function using AnadigmDesigner®2 software, its configuration is simply achieved by transferring the associated configuration data file, via serial cable, and program a serial EPROM on the starter kit with that data file, and then the FPAA can configure itself on power-up from that EPROM [2]. This kind of configuration is known as the static configuration, which is usually used for applications where the required analog circuit behaviour is known beforehand. However, for applications in which analog behaviour must be adjusted on-the-fly without the need to reset the FPAA, AnadigmDesigner®2 offer convenient methods (using C code) for a host processor to access and change the configurable parameters of the CAMs used in the configuration, while the FPAA is working. Then, the changed data are stored in an on chip SRAM memory, which support multiple configurations to be loaded over time if necessary [1]. This configuration is known as the dynamic reconfiguration, which can
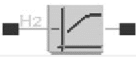
be employed for partial or total reconfigurations, here it is worth noting that this operation needs only one clock cycle to be achieved, and thus to offer a high flexibility of prototyping to the FPAA circuit user.

## IV. FPAA CONFIGURATION AS ECG SIGNAL CONDITIONING BLOCK

As previously mentioned in this chapter, the ECG signal front-end element architecture was inspired from [1], and has been built using the available CAMs in the AnadigmDesigner®2 library. Actually this architecture is composed of:

✓ A selected input cell configured as an input cell chopper amplifier used at its highest gain of 128, this amplifier presents a typical high resistor of (10 MOhm), a very low input voltage (100µV), and a high CMRR (102 dB). With association to the input amplifier, an anti-aliasing filter configured with the minimum corner frequency allowed by Anadigm (76 kHz) was used to eliminate the noise generated by the chopper amplifier switching clock. In this arrangement, the chopper amplifier is governed by a 250 KHz clock.

✓ A high pass filter that attenuates DC component and baseline wandering has been implemented using a bilinear one pole filter CAM. This high pass filter is a first order filter, configured with unity gain and a low corner frequency to achieve the desired cut-off frequency of 0.05 Hz. Here the high pass filter was governed by a frequency clock set to 0.490 KHz.

*Tab IV.1. The different FPAA CAMs used for realizing ECG signal Front-end element*

| Name | Options | Parameters | Clocks |
|---|---|---|---|
| FilterBilinear1 | Filter type: high pass Resource usage: low corner frequency | Corner frequency [Hz]: 0.245 Gain: 1.00 | Clock A: 0.490 kHz (Clock 3) |
| FilterBiquad1 | Filter type: band stop Filter topology: automatic | Corner frequency [Hz]: 50.1 DC gain: 1.000 High frequency gain: 1.000 Quality factor: 30.0 | Clock A: 7.352 kHz (Clock 2) |
| FilterBilinear1 | Filter type: low pass Resource usage: minimum resources | Corner frequency [Hz]: 150 Gain: 8.00 | Clock A: 125 kHz (Clock 1) |

✓ A unity gain notch filter employed to eliminate the AC line interference implemented using a bi-quadratic two poles filter CAM, this band stop filter is configured with a high quality factor Q=30, and governed by a switching frequency clock set to 7.352 KHz which allows the band-stop center frequency to be set to 50 Hz.

✓ A low-pass filter that eliminates noise components over 150 Hz has been developed using a Bilinear Filter CAM in low-pass configuration and with its gain set to 8. The switching clock for this module is set to 125 kHz. This is the highest frequency that allows setting the filter corner frequency to 150 Hz. This election enables the anti-aliasing filter hosted in the output cell to eliminate the noise generated by the switched capacitors within this CAM.

The implemented architecture using the CAMs components provides a good gain varying between 60 dB and 66dB (1000 to 2000), and a good signal to noise ratio. Table.IV.1 summarizes the deferent used CAMs and their configured parameters. Thus, as shown in Fig IV.2, The implementation into the AN221E04 FPAA circuit, consumed 50 % of the chip recourses, by using the all capacitors and operational amplifiers of two CABs among the four CABs originally constituting the FPAA circuit, one input cell and one output cell.
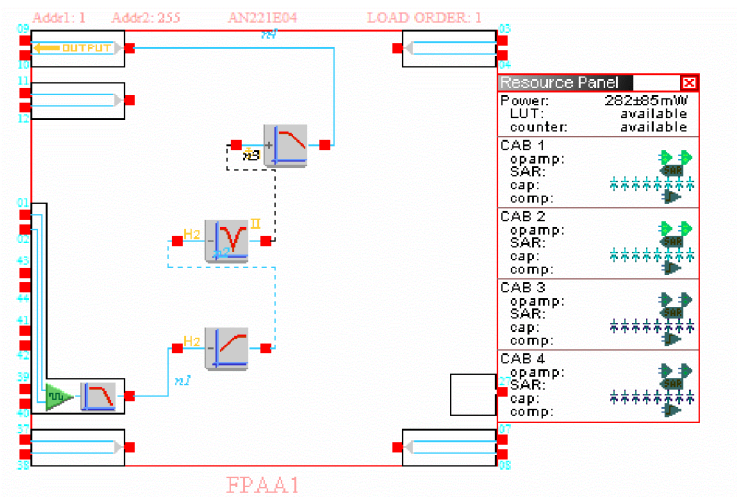


*Fig IV.2:* *Anadigm view of the FPAA configuration.*

Before moving to the Immunity test, the first step to do is to obtain the frequency and time responses of the actual analog configuration of our FPAA.
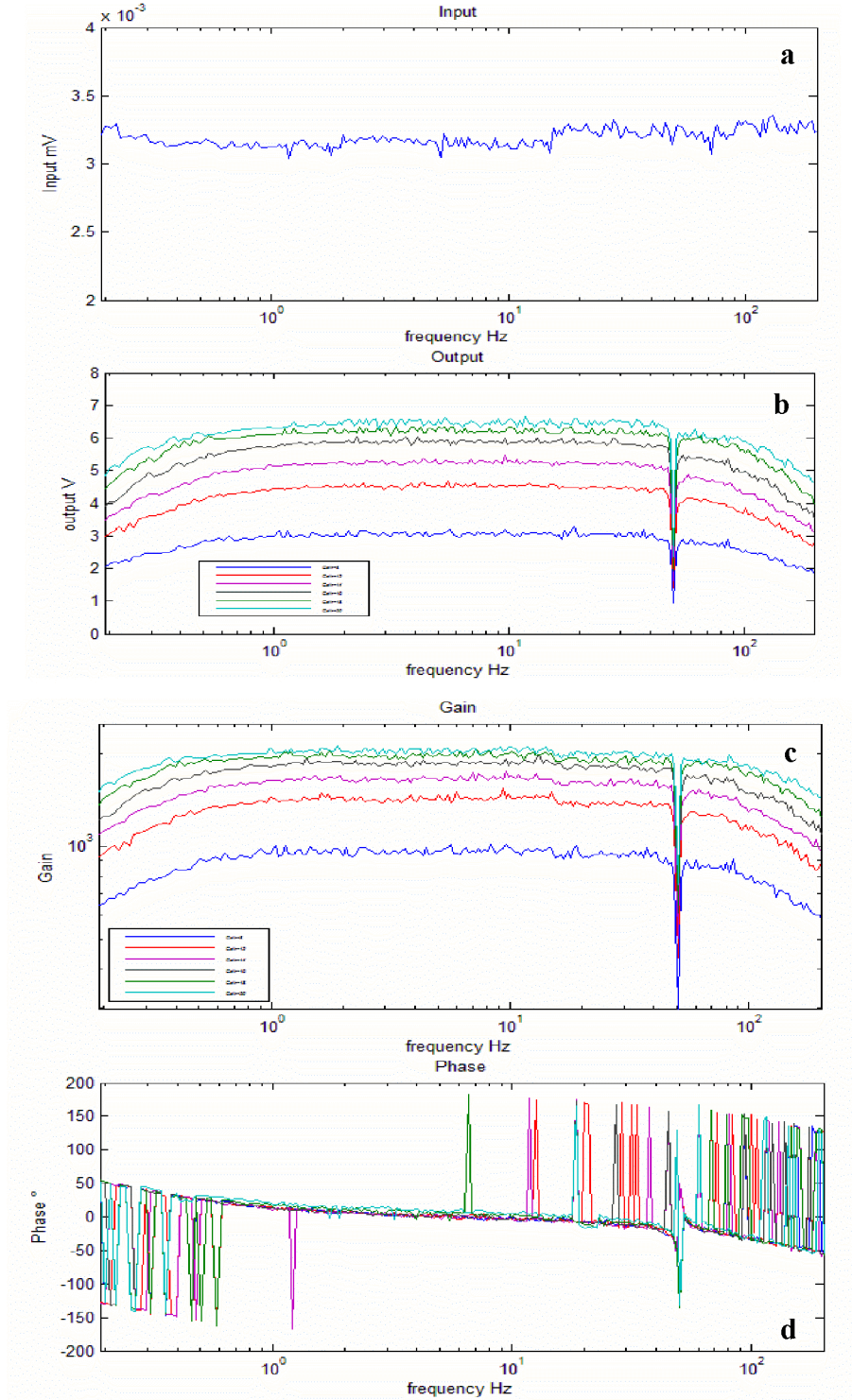


*Fig.IV.3*: Nominal conditions measurements: a) Input signal amplitude. b) Output signal amplitude for variable gain values. c) The different system gain possible values. d) The phase shift regarding the different system gain values.

Fig.IV.3 depicts the measurement of the input/output amplitude, phase shift, and the experimental Gain (or Bode diagram) for different Gain configurations, showing the typical bandwidth from 0.2 Hz to 150 Hz, thus allowing diagnostic uses according to EC-38 standard [3]. Fig.IV.4 shows a typical time response of the system. This data has been obtained with a generic ECG pattern from the Agilent 33120A signal generator configured to low amplitude of 30 mVpp and 60 bpm (beats per minute). This signal is plugged into the FPAA device through a resistive divisor, in order to obtain the typical 3 mVpp ECG amplitude.

On those measurements some observations that we should mention:

✓ Using the same FPAA configuration and changing the value of the parameter gain in the low pass filter (which effect directly the whole system Gain value), from value 8 to the maximum allowed by Anadigm 20, the actual FPAA configuration can provide a very good amplification up to 66 dB and good filtering. However, reaching the maximum gain value of 20, the FPAA presents saturation behaviour and a distortion be observed on the output signal.

✓ The system is presenting a good stability and the phase shift between its input channel and output channel is quite stable besides the some discontinuities that we can observe on the graph, and which are caused by the bad synchronization between the generator and the Oscilloscope used to perform those measurements.
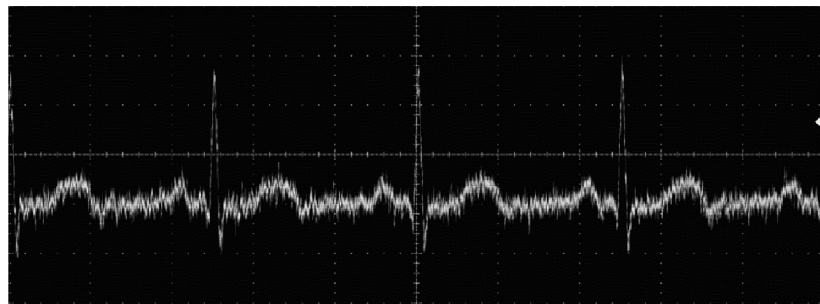


*Fig.IV.4*: *time response of the system.*

- ✓ The acquisition time needed to acquire the whole system response is about 1 hour and 30 minute, due to the nature of the very low frequency signal we are dealing with, and also, to the use of 2 % step size to cover the total range of frequencies from 0.1 Hz to 200 Hz (which cover the diagnosis frequency range), which mean acquiring 214 measurement points. However, in the rest of this study we will focus on the interval of 0.5 Hz to 60 Hz, which cover the specific 0.67 Hz to 40 Hz monitoring frequency band and the 50/60 Hz power line frequency, in order to reduce the time of measurement points to only 154 points.

- ✓ However, despite the lack of further digital processing for the generic ECG signal used in this measurement, the P-QRS-T wave is perfectly distinguishable in Fig.IV.4 and the analog processing provides useful ECG data, ready for digital processing.

# V. FIRST EXPERIMENT

## V.1. TEST METHODOLOGY

In this first experiment, the immunity test we performed was based on a differential approach proposed by Aldo Baccigalupi et al in [4], where the experimental measurements were enrolled into two phases. The first phase consists of measuring the input/output signal amplitude, phase shift and the gain of the system at nominal condition (the absence of any external disturbance). And, in the second phase, the same measurements were taken at the presence of an Electromagnetic energy radiating on the device under test (DUT) inside a G-TEM cell. Then, we consider the difference between the two measurements as the effect of the interference. This approach is represented in the schematic of the Fig.IV.5. Here, it is important to mention that the used GTEM cell is a waveguide in which a linearly-polarized transverse EM field can be generated with amplitude uncertainty up to 6 dB within the work volume. Before proceeding the immunity test measurements, this GTEM cell was calibrated unloaded (without the DUT inside) to determine the power needed to obtain the EM field amplitude over the test frequency range, always by following the prescription on the IEC EN 61000-4-20 standard.
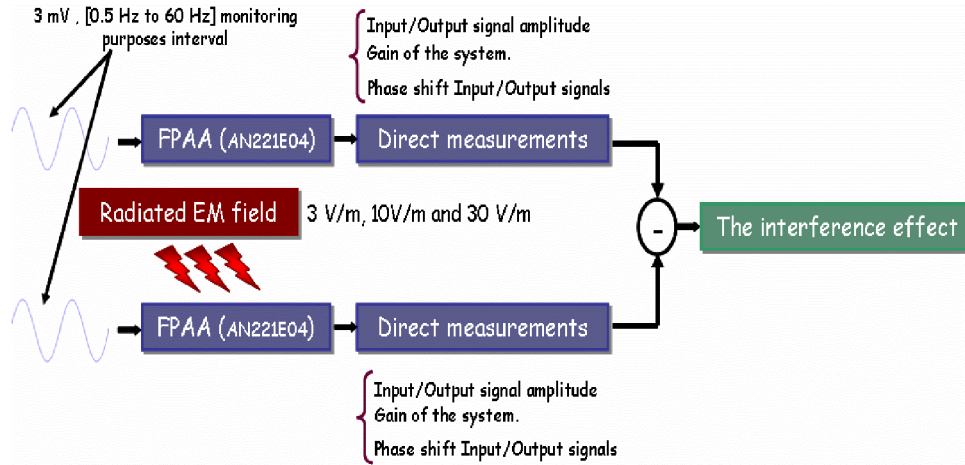
*Fig.IV.5*: *The representation of the differential approach methodology employed in the first test experiment*

The FPAA was fed with a 3 mV sine-wave signal of frequency range from 0.5 Hz to 60 Hz to cover the range from 0.67 Hz to 40 Hz that is specific to ECG monitoring applications [3] and the 50/60 Hz power line frequency. At the second phase, the test measurements were performed at the presence of an EM radiation of different intensities 3 V/m, 10 V/m and 30 V/m spanning the frequency interval from 80 MHz to 3 GHz, with step of 1% of the fundamental frequency, and amplitude-modulated to 80%-depth 1 kHz signal, as indicated in EN 61000-4-3[5] and EN 61000-4-20 [6] standards.

## V. 2. RESULTS

### V. 2. 1. First phase: nominal conditions measurements

The measurements done in this phase are considered as reference to the next measurements steps. Here, the FPAA was fed with a 3 mV sine-wave signal of frequency range from 0.5 Hz to 60 Hz to cover the ECG monitoring applications range from 0.67 Hz to 40 Hz. As it is shown in Fig.IV.6, at each frequency step, we acquired the amplitude of the signal in the input/output channels, the phase shift between them, and we processed the gain of the system, which correspond to the ratio between the output amplitudes and the input one, since the system is linear.
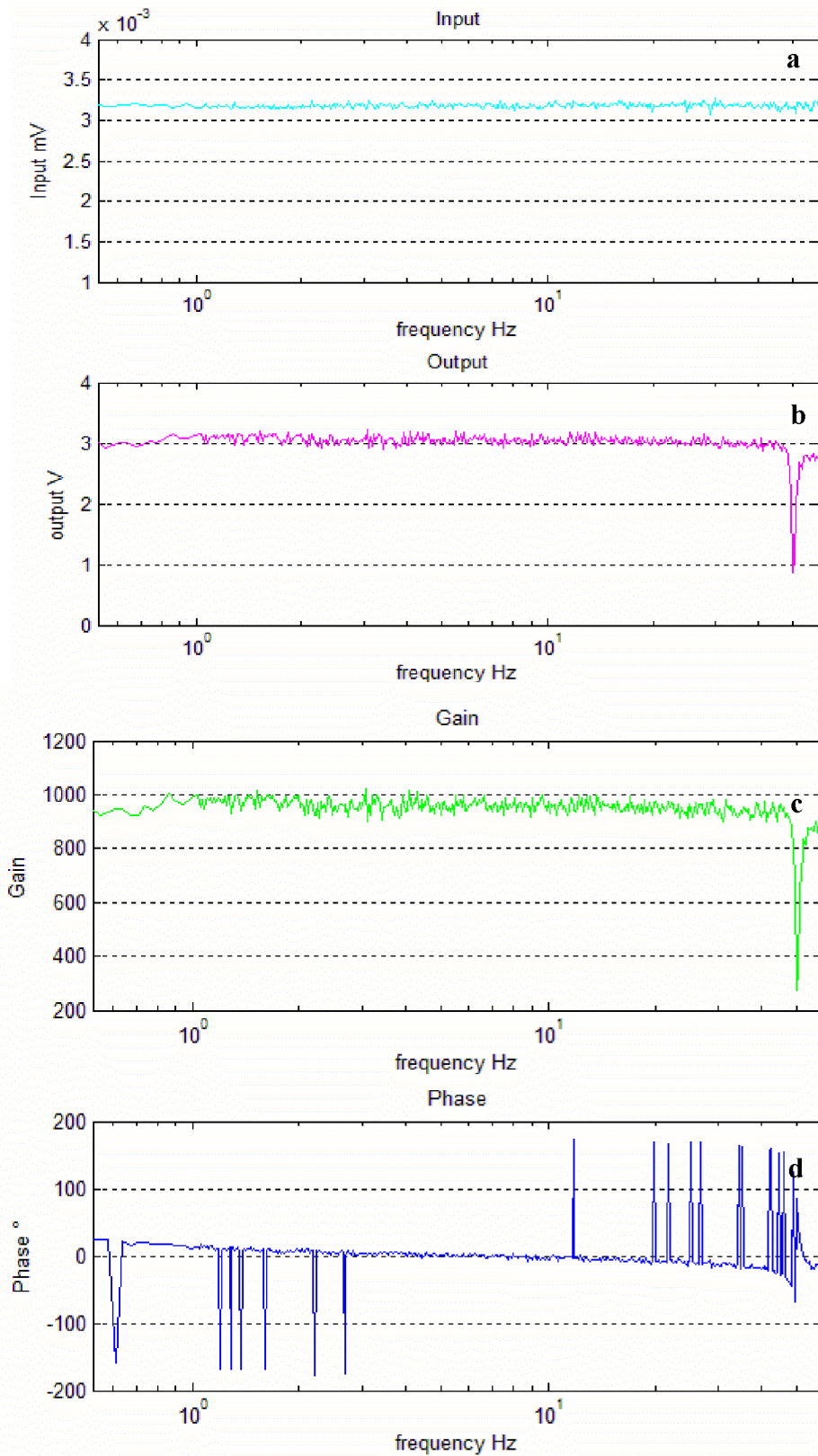
***Fig.IV.6***: *The nominal condition measurements for the ECG monitoring frequency range [0.67 Hz to 40 Hz]. a) Input signal amplitude. b) Output signal amplitude for variable gain values. c) The different system gain possible values. d) The phase shift regarding the different system gain values.*

## V.2. 2. SECOND PHASE: MEASUREMENTS UNDER INFLUENCE OF EM RADIATED ENERGY

This experimental phase consists of the evaluation of the FPAA susceptibility (immunity) to external Electromagnetic EM radiation. Here, we followed the methodology described in the EN 61000-4-3 [5] and the EN 61000-4-20 [6] standards to carry on the test. Those standards prescript a set of different steps to follow, in order to test the EM compatibility of electronic devices by examining their ability (immunity) to function in the presence of EM disturbances. Actually, there are two principle steps to follow:

The first step consists of the calibration of G-TEM cell without the circuit under test (CUT) in it, by using the PMM OR03 programmable optical repeater probe, to determine the necessary power to set on the function generator to generate the desired EM field amplitude over the target frequency range. The G-TEM cell used here is a waveguide cell with linear polarization which generates a transverse electromagnetic (TEM) field with amplitude uncertainty up to 6 dB within the working volume.

The second step consists of placing the CUT (the starter-kit on which the FPAA is mounted) inside the cell at the same distance from the source of EM field generation (inside the G-TEM cell) as the probe was placed in the calibration phase, and executing the test on the FPAA by using the obtained calibration power values, thus to obtain the target EM field amplitude value (3 V/m, 10 V/m and 30 V/m) over the range of frequency from 80 MHz up to 3 GHz, with step of 1% of the fundamental frequency. The generation of the EM filed and the measurement of different desired quantities in this test are insured by the mean of instrument installation as shown in Fig.IV.7. This installation is controlled by a computer using Labview tool and GPIB protocol to communicate with the different instruments. Here, the EM field was generated by an Agilent E4438C signal generator and amplified by the two Bonn Elektronik amplifiers, the FPAA was supplied by an Agilent E3648A dual output DC power supplies and feed by a 3 mV sine wave, generated by an Agilent 33220A function generator, and the different input/output waveforms were acquired using the Agilent Infiniium 54833D MSO oscilloscope. However, the measurements were done by the

reconstruction of different saved signals on the computer using Labview programming. It is important to note that, in this test phase, the EM field is typically amplitude modulated with a 1 KHz sine wave to a depth of 80 %.
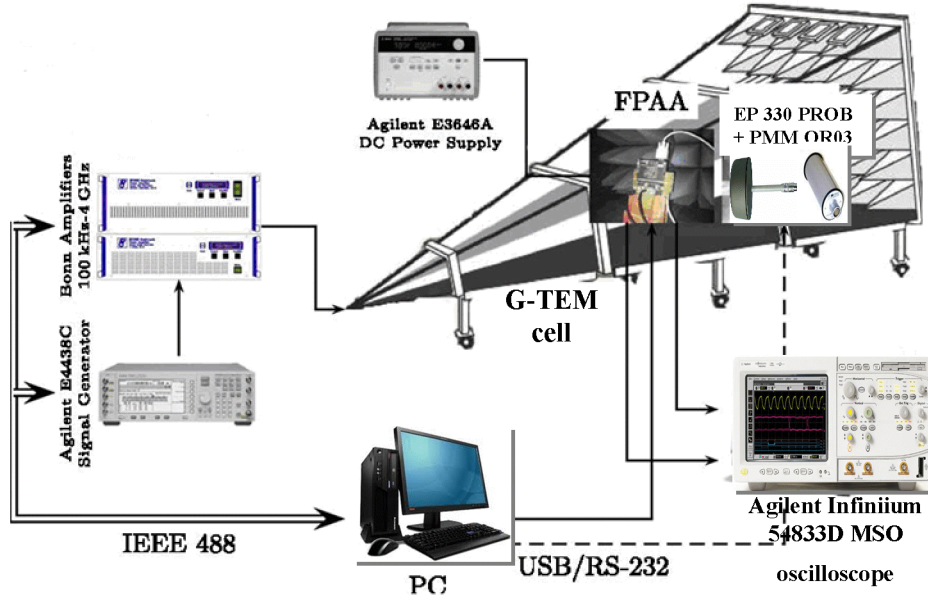


*Fig.IV.7*: *The test experimental installation.*

As previously mentioned, this test was performed for different EM field amplitudes, 3 V/m, 10 V/m, and 30 V/m. The resulting measurements revealed different responses behaviour of our FPAA-based biomedical application to the external disturbance.

## V. 2. 2. 1. 3 V/M TEST

As shown in Fig.IV.8, it is clear that radiating our DUT using a 3 V/m Electromagnetic field has an effect on the FPAA input/output channels. This effect manifests as a slight amplification on the input signal and as an attenuation on the output signal, and is significantly clear for sinusoidal signal frequencies above 12 Hz. However, the Gain representation shows that this effect is observed as a very small attenuation of the system gain except for the pick attenuation value we can notice on the sinusoidal signal frequency around 12 Hz (- 4dB).
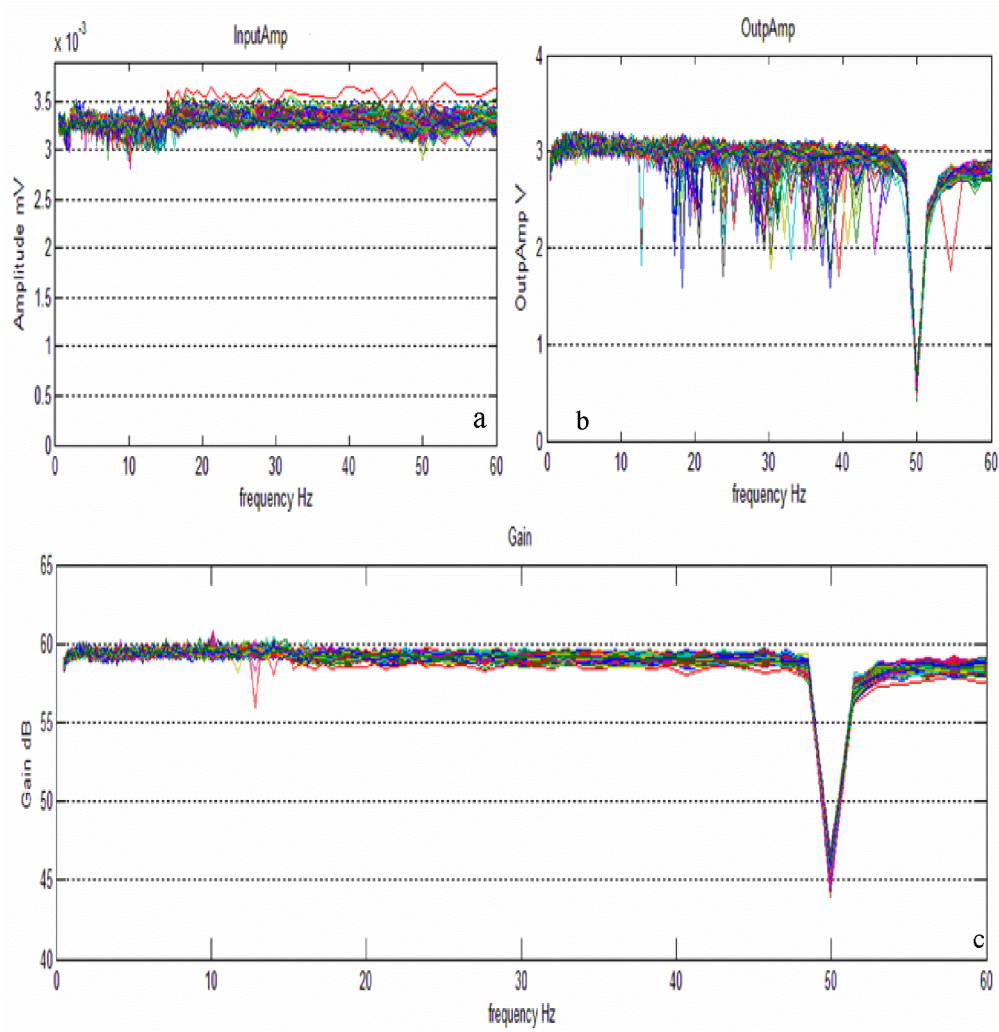
***Fig.IV.8***: *The detection of the 3 V/m EM radiation effect on: a) Input channel. b) Output channel. c) System Gain.*

To identify the disturbance frequencies responsible of this effect, we processed in such way to measure at each generated EM frequency, the maximum difference between the obtained measurements of each parameter and those obtained in the first phase of measurements (at nominal conditions) using Matlab tool. Thereby, we could also spot the amount of disturbance which caused the amplification on the input channel and the attenuation on the output channel. This amount of disturbance is referred to us as the additive noise.
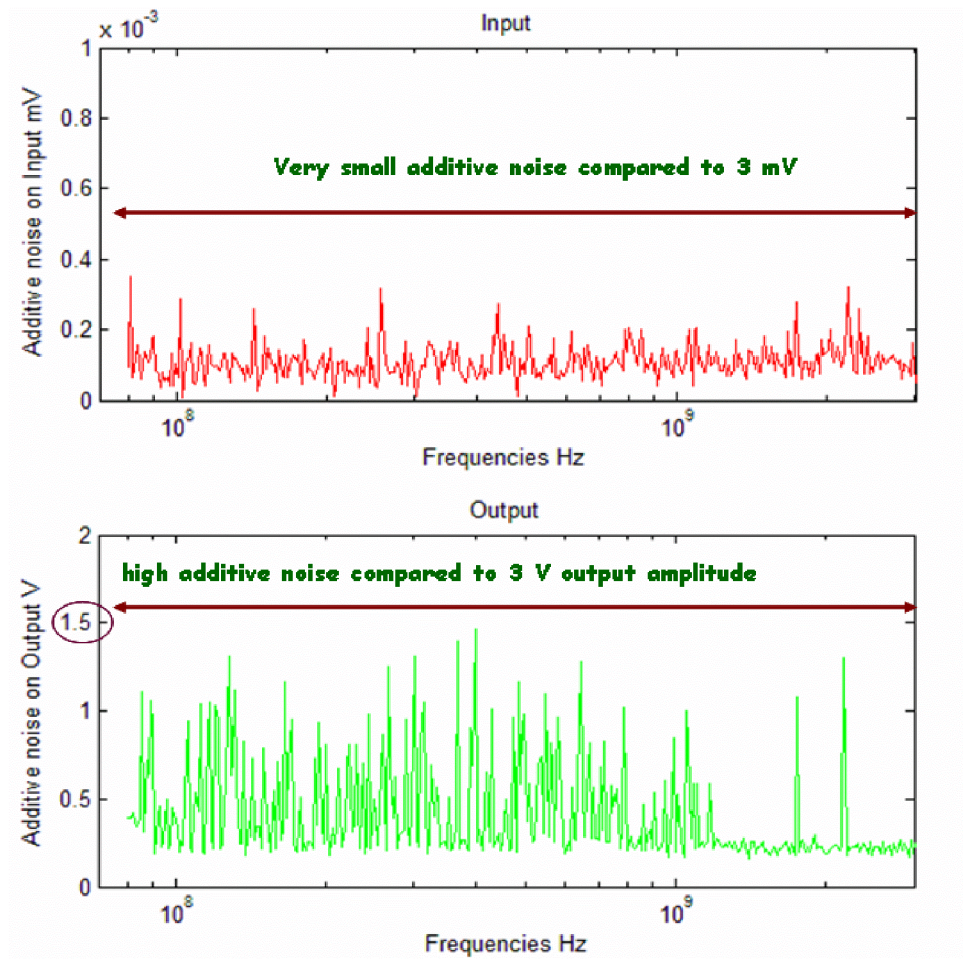
**Fig.IV.9**: *The additive noise caused by the 3 V/m EM radiation on: a) Input channel.*
*b) Output channel.*

The Fig.IV.9 represents the additive noise on the Input/output channels (quantization of the EM radiation effect). It shows the small (compared to the 3 mV feeding the FPAA) noise on the input channel is of the order of some hundred of micro volts, thus all over the test frequency interval [80 MHz to 3 GHz]. However, on the output channel the disturbance was distributed all over the frequency range from 80 MHz to 1.1 GHZ with a pick value of 1.5 V around 400 MHz and two distinguishable picks in the rest of the frequency range up to 3 GHz. In reality, this quantization of the EM radiation effect on the output channel represents the amount of the attenuation of the signal on the output observed in the preceding figure corresponding to the EM radiation frequencies causing that attenuation.
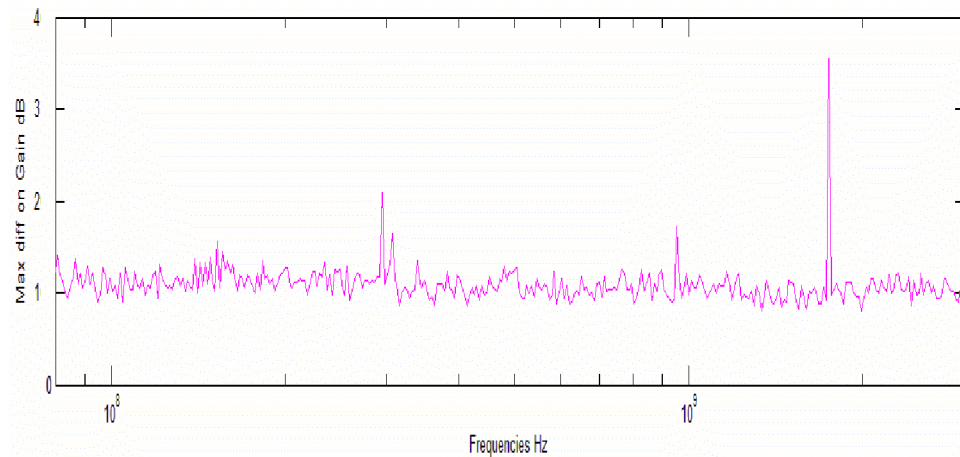
***Fig.IV.10****: The effect of the 3 V/m EM radiation on the system gain.*

Fig.IV.10 shows that the average attenuation on the system gain (observed on Fig.IV.8.c) is around 1 dB all over the frequency rage 80 MHz to 3 GHz, accept for the tow distinguishable picks at respectively 300 MHz and 1.8 GHz (2 dB and 3.6 dB), which correspond to the maximum gain attenuation observed on Fig.IV.8.c).

In this case, the disturbance caused by the 3 V/m EM radiated energy on our DUT, can be considered as not important since it does not cause a serious damages to the system function, even if that effect is quite important on the output channel,

## V. 2. 2. 2. 10 V/m Test

Using a 10 V/m EM field to radiate our DUT, and performing the same test steps as in the previous experiment, we noticed that the effect of this disturbance has deferent aspect compared to the first test using the 3 V/m EM radiation. Fig.IV.11 shows a clear effect on both input and output channels, exhibiting amplification on both channels in particular for input sinusoidal signal frequencies above 15 Hz. This effect is more important on the input channel. However, looking to the gain representation, we can notice the slight amplification on the first part of the graph (from 0.5 Hz to 15 Hz) which turn suddenly at the input signal frequency of 15 Hz, to an attenuation (not significant), thus all over the frequency interval from 15 Hz to 60 Hz.

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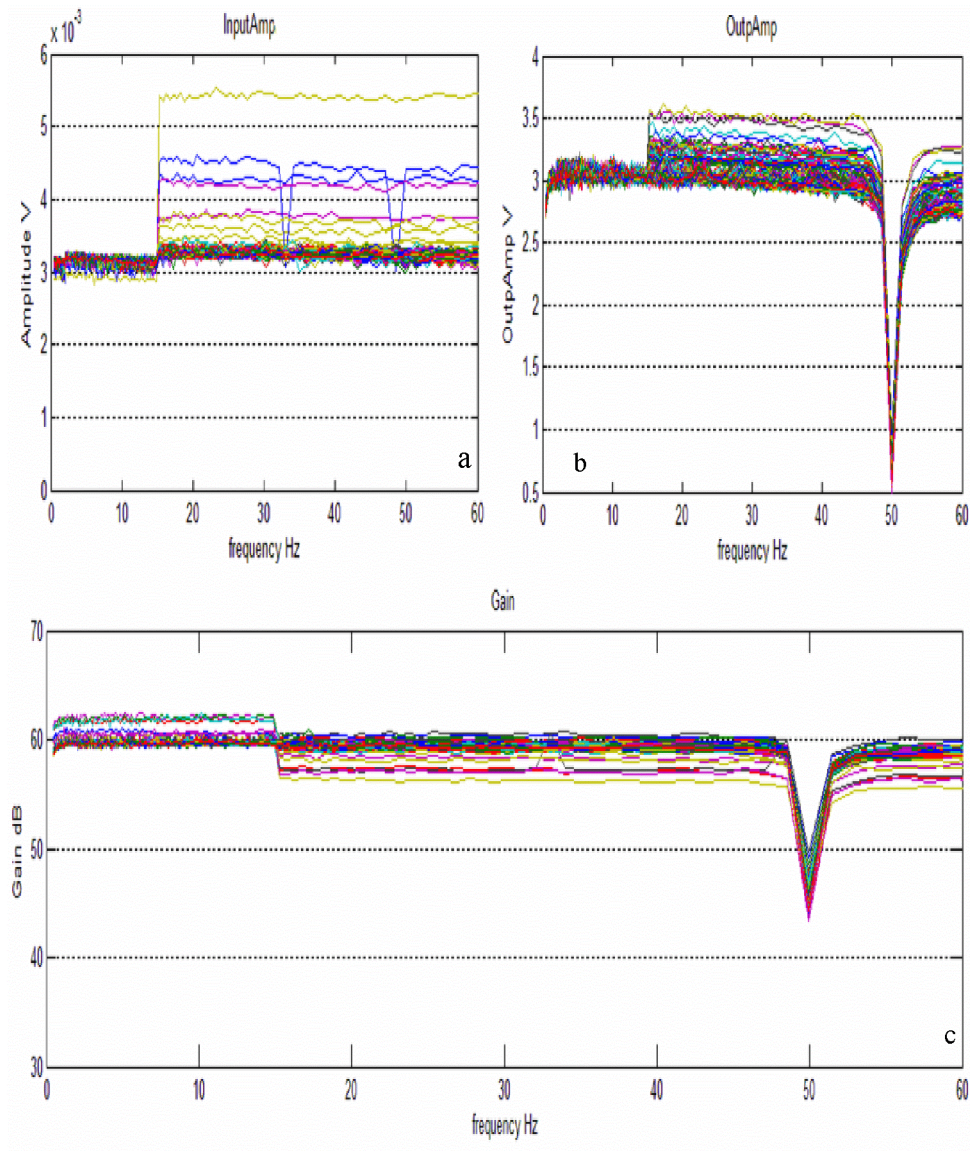
***Fig.IV.11****: The detection of the 10 V/m EM radiation effect on: a) Input channel.
b) Output channel. c) System Gain.*

The detection of the EM radiation frequencies responsible of this effect
identifies a specific band of frequencies [100 MHz to 300 MHz], in which
the effect is significant on both input/output channels. Fig.IV.12 represents
that effect (the additive noise). Here, the present noise on the input is more
important then its presence on the output channel with distinguishable pick
values of 2.4 mV, 1.4 mV and 1 mV respectively at around 127 MHz, 170
MHz and 200 MHz on the input channel. And, 0.6 V and 0.4 V in the same
range of frequencies as on the input channel.
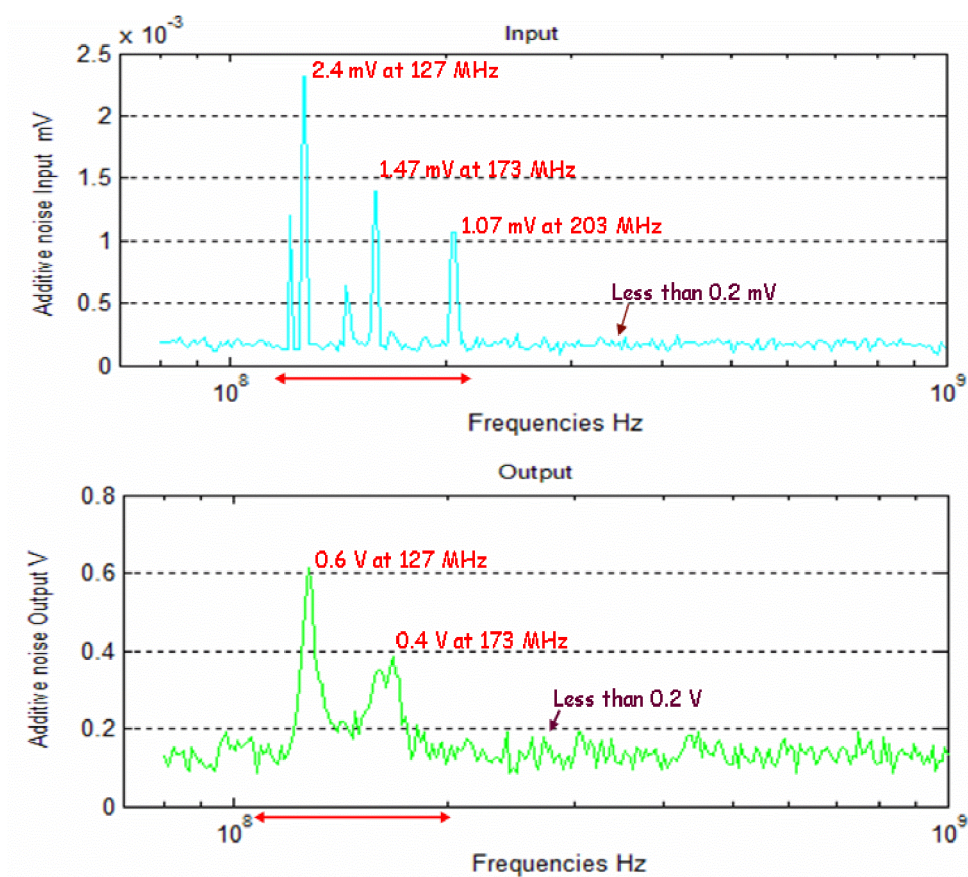
***Fig.IV.12***: *The additive noise caused by the 10 V/m EM radiation on: a) Input channel.*
*b) Output channel.*

Fig.IV.13 represents the effect of the 10 V/m EM field disturbance on the system gain, which behave in the same way as its behaviour on the input/output channels. Pick values of almost 4.1 dB and 3.7 dB were detected in the same frequency interval [100 MHz to 300 MHz]. These values represent the maximum attenuation on the system gain cause by the actual disturbance.
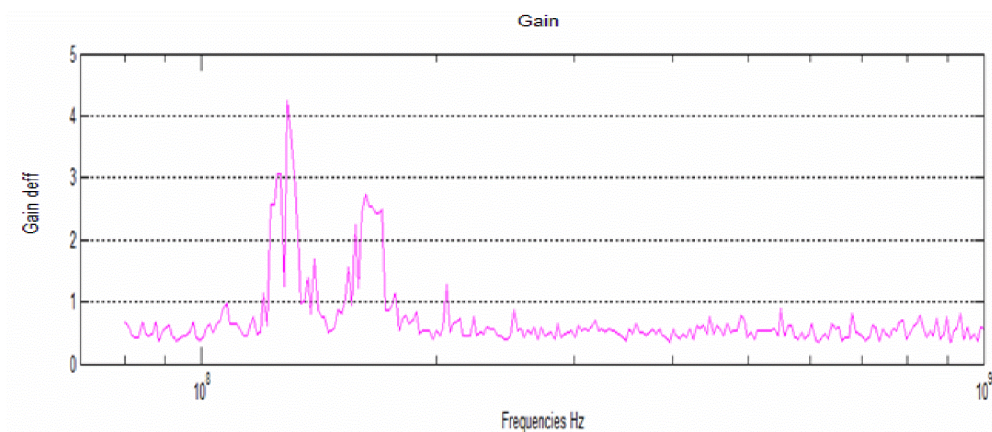


***Fig.IV.13***: *The effect of the 10 V/m EM radiation on the system gain.*

Here, it is clear that a disturbance of 10 V/m EM radiated energy, has a significant effect on the FPAA input/output channels only within the interval of frequencies going from 100 MHz to 300 MHz, with more significant noise on the input channel. However, this effect can be considered not affecting really the FPAA function, since the attenuation on the system gain is only about 4 dB (compared to the system gain of 60 dB).

## V. 2 .2. 3. 30 V/m Test

Arriving to 30 V/m EM field disturbance level, the interference was important that we couldn't localize precisely the maximum measurements values we needed using a direct measurement (reading on the oscilloscope), because of the huge noise and the important offset shift especially on the input channel. Moreover, the 1 kHz modulation on the radiated field was also clearly visible at both the input and output terminals as shown in Fig.IV.14.
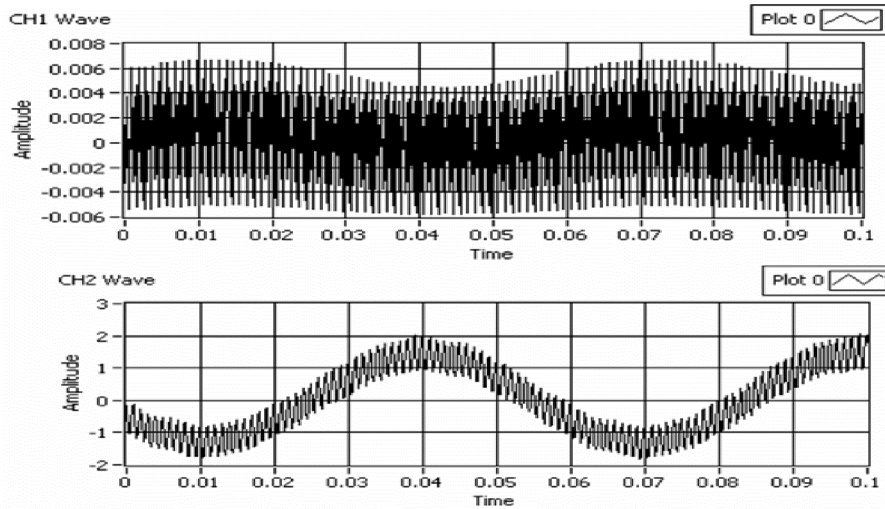


*Fig.IV.14*: The observed modulation caused by the 30 V/m EM radiation on: CH1) Input channel, CH2) Output channel.

To bring out the different effects measurement in this case, we processed an FFT transform analysis on the input/output signals. Thereby, we could precisely identify the maximum values at different EM radiation frequencies of the important offset shift value (Fig.IV.15) and trace the harmonics corresponding to the modulation present particularly on the input signals (example shown on Fig.IV.16).
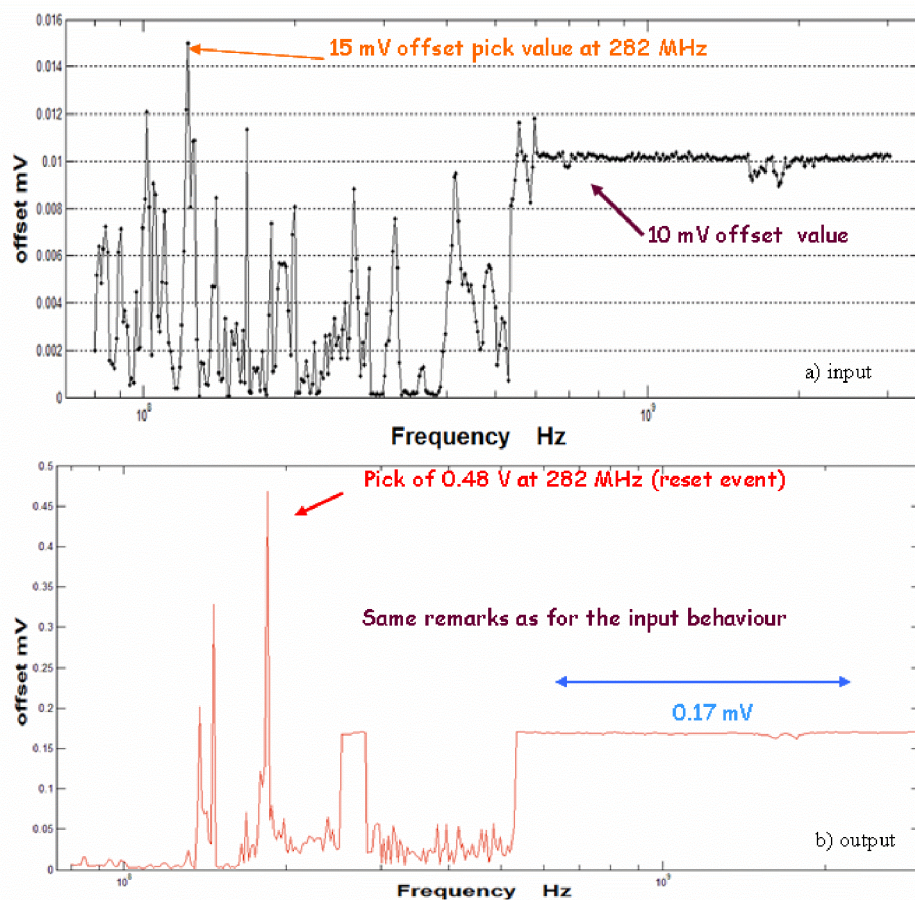
***Fig.IV.15***: *The detected offset caused by the 30 V/m EM radiation on: a) Input channel.*
*b) Output channel.*

It is also important to note that at frequencies between 250 MHz and 282 MHz the interference was so large to cause the FPAA to reset and the configuration to be written off so that the output was 0 V.



***Fig.IV.16***: *The different superposed distorted modulating harmonics detected on the input channel at EM frequency of 245 MHz.*

## V. 3. FIRST EXPERIMENT OBSERVATIONS

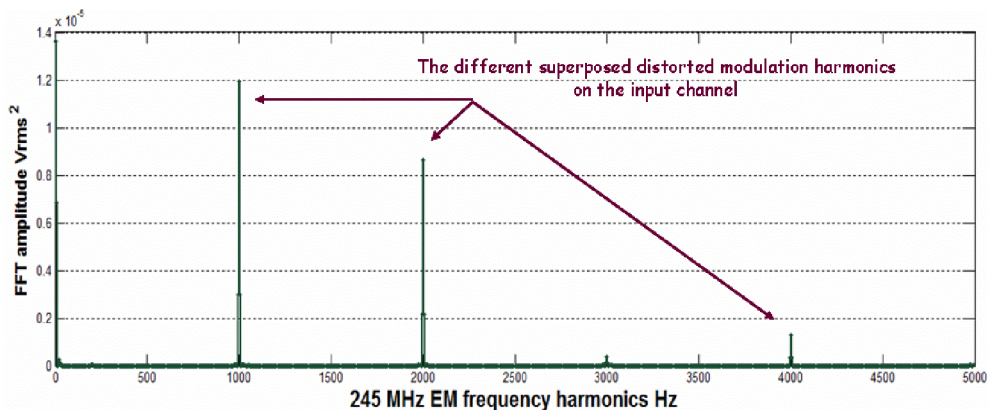This first experiment, which consists of a formal immunity test to assess the FPAA-based biomedical application function to EM radiated energy, revealed some observations worthy to be taken in account, which are:

- ✓ The greater the EM radiated energy, the greater is the effect on the FPAA Function.

- ✓ Higher EM field disturbance don't only add noise to the useful signal, but it causes the system to behave in a non linear way.

- ✓ Lower EM field frequencies are more affecting the system function than the highest ones.

- ✓ The worst interference on the FPAA function was the reset event observed for EM field of 30 V/m within the frequency range from 252 MHz to 282 MHz, in which the FPAA configuration was written off and the output channel was indicating 0 V.

- ✓ The elapsed time to carry out the necessary measurements for this experiment was very long, since the used input signal was very slow, and also because of some instructions imposed by the test standards methodology (1% of the fundamental frequency step), for both signal frequencies (the used sinusoidal input signal, and the EM disturbance frequencies). This time is about 10 days of non stop measurements (if no incident happen like power supply cut off) to cover the whole frequency range 80 MHz to 3 GHz for one EM field amplitude (3 V/m or 10 V/m or 30).

## VI. SECOND EXPERIMENT

### VI. 1. TEST METHODOLOGY

Unlike the requirements of the methodology described in the IEC EN 61000-4-3 followed in the first experiment, the actual immunity test we performed was based on a new approach in which we used a generic ECG waveform of 1 Hz frequency generated by an Agilent 33220A arbitrary waveform generator, to feed the device under test (DUT), and we employed the FFT as a reliable means to process the signal in frequency domain to

measure the maximum amplitude, the phase and the offset of the ECG signal on the FPAA input/output channels as shown in Fig.IV.17. here, the test measurements ware performed at the presence of EM radiation (3 V/m, 10 V/m, 20 V/m and 30 V/m) inside a GTEM cell within a frequency interval from 250 MHz up to 3 GHz, and using two different amplitude modulation: 1 kHz (according to the EN 61000-4-3 standard, for the functional test) and 2 Hz (according the EN 60601-1-2, for biomedical instrument test).
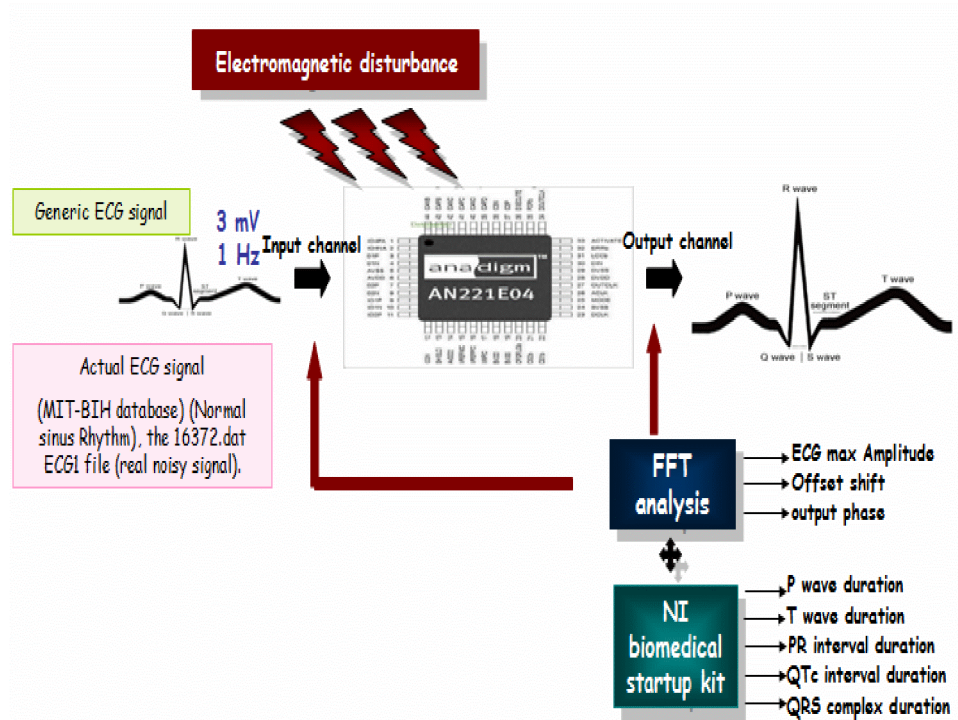


*Fig.IV.17*: *The representation of the second test methodology.*

Moreover, using the National Instruments biomedical start-up kit, we performed a time domain analysis, where we measured for each EM frequency the time durations of the different parts of the ECG signal, namely: the P wave, the QRS complex, the PR and QT (QTc) intervals, in order to investigate any kind of modification the EM disturbance can cause to these parameters concerned by the electrical conduction system of the heart and which are crucial in monitoring and diagnosis operations.

Actually, the evaluation of the change on these parameters is based on comparing the obtained measurements for each one of them to the nominal values cited in medical bibliography [7].

On the other hand, the evaluation of the additive noise on the FPAA input/output returns to measure the difference between the maximum amplitude detected and the mean value of ECG signal amplitude measured using the biomedical start-up kit. Moreover, phase shift and offset shift have been taken in account at each EM disturbance.

This test was performed one time using a generic ECG signal generated by Agilent 33220A arbitrary waveform generator, and a second time using an actual ECG signal downloaded from MIT-BIH Normal sinus Rhythm database the 16372.dat ECG1 file (real noisy signal) [8]. The two signals are 3 mVpp amplitude, 60 bpm frequency and 0 V offset.

## VI. 2. RESULTS

Here, we distinguish two measurement parts, the first one concern the results of the frequency domain analysis using the FFT transform, which allowed us to identify the maximum amplitude of the signals on the FPAA input and output channels, the phase shift between them and the offset, and also to spot the nonlinear behavior of the FPAA circuit, with localizing the different harmonics of the 1 KHz (2 Hz) modulation frequency carried on both channels. However, the second part concern the results of the time domain analysis using the NI biomedical startup kit VIs [9], to investigate and identify eventual modifications, the EM radiation can cause to the time duration of the different parameters on ECG signal (previously cited).

### VI.2. 1. FREQUENCY ANALYSIS RESULTS

#### VI.2. 1. 1. THE ADDITIVE NOISE

##### VI. 2. 1. 1. 1. GENERIC ECG SIGNAL

As previously mentioned, the additive noise presented on Fig.IV.18, and Fig.IV.19, is calculated using the differential approach inspired from [4], and used in the first experiment (section V.2). The quantity of this additive noise represents the difference between the maximum amplitude of the of the signal (useful one plus noise) that we measured using FFT transform,

and the mean value of the ECG signal calculated by the NI biomedical startup kit VI, and that on both FPAA channels, input and output.



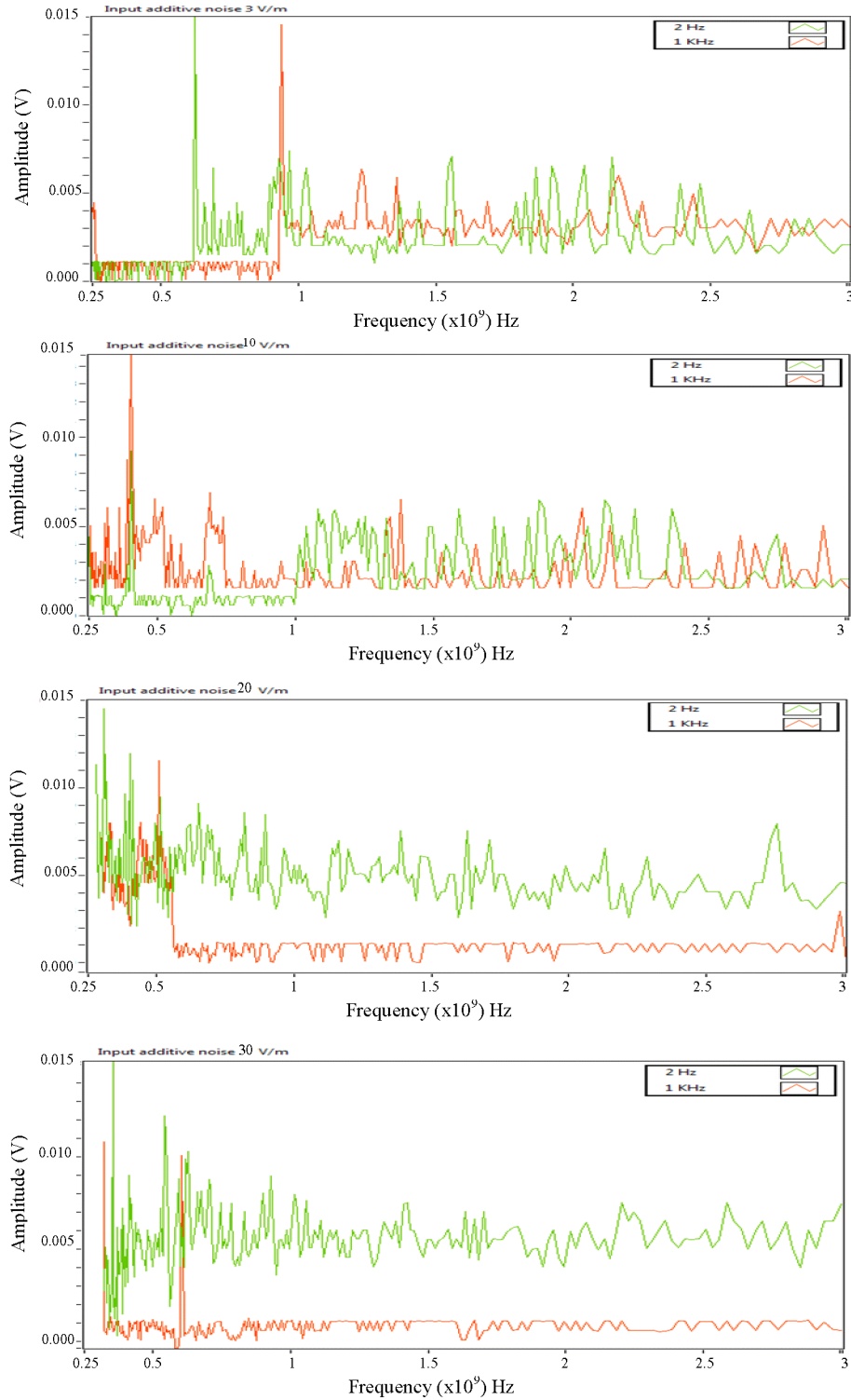***Fig.IV.18***: *The additive noise detected on the FPAA input channel at the different EM radiated energies (3, 10, 20 and 30 V/m), for the two used amplitude modulations 2 Hz and 1 KHz. This measurement is obtained using the generic ECG signal*

Fig.IV.18 shows the evolution of the additive noise on the FPAA input channel for the two used amplitude-modulation frequencies 2 Hz (green color) and 1KHz (orange color) over the for EM used radiations (3 V/m, 10 V/m, 20 V/m and 30 V/m). As we can notice, this additive noise behaves differently regarding the used amplitude-modulation frequency:

- At the 3 V/m EM radiation, there was kind of slight attenuation of the ECG signal during the lower part of the disturbance frequencies for both used modulations frequencies, and then, suddenly this attenuation became a real additive noise all over the higher EM disturbance frequencies from around 900 MHz to 3 GHz for the 1 KHz used amplitude modulation, and from around 700 MHz to 3 GHz for the 2 Hz amplitude modulation. Here, this additive noise which can reach 15 mV (correspond to five times the input signal amplitude) at EM radiation frequency of 700 MHz for 2Hz modulation (900 MHz for 1 KHz modulation), is qualified as a very high noise compared to the 3 mV amplitude of the used input signal feeding the FPAA circuit.

- At the 10 V/m EM radiation, the additive noise become more important using the 1 KHz modulation than the one measured using 2 Hz modulation between 250 MHz and 1 GHz, with a pick value of 14 mV for both used modulations on the input signal at EM radiation frequency around 400 MHz. however, beyond the EM radiation of 1 GHz and up to 3 GHz, the additive noise measured for 2 Hz modulation become more important and more consistent compared to the one measured for 1 KHz modulation.

- At 20 V/m EM radiation, the additive noise is higher and more consistent all over the test frequency range for the used 2 Hz amplitude- modulation than the one measured for 1 KHz modulation, thus, pick values are detected at EM radiation frequencies around 300 MHz (14 mV) and around 400 MHz (12 mV), for the remaining test frequency interval, the average value of the additive noise is about 5 mV. Moreover, using the 1 KHz amplitude-modulation, the additive noise is detected only on the

input signal at the EM radiation frequencies from 250 MHz to 600 MHz, and then the interference effect become a kind of signal attenuation (small attenuation) up to EM radiation frequency of 3 GHz.

- At 30 V/m EM radiation, the interference effect of this disturbance is totally different regarding the used amplitude modulation. For 2 Hz modulation a high additive noise is measured all over the test frequency range, with detected pick values of 14 mV, 12 mV and 10 mV at respectively 280 MHz, 330 MHz and 500 MHz, and an average value of 6 mV for higher EM radiation frequencies up to 3 GHz. While, for 1 KHz modulation the interference effect manifested this time as a kind of attenuation of the input signal, which can reach 2 mV at lower EM radiation frequencies except for two frequencies 250 MHz and 582 MHz, where a very high additive noise of about 10 mV and 11 mV was detected. It is important to point out that attenuation of 2 mV is very high attenuation comparing it to the input signal amplitude of 3 mV.

Fig.IV.19 represents the evolution of the additive noise on the FPAA output channel for the two used amplitude-modulation 2 Hz (green color) and 1KHz (orange color) over the for EM used radiations (3 V/m, 10 V/m, 20 V/m and 30 V/m). Here, the additive noise on the output channel seems to be stable and have the same behavior for both used amplitude modulation frequencies 2 Hz and 1 KHz at 3 V/m and 10 V/m EM radiation, it is about 150 mV to 300 mV all over the test frequency range, except for some pick values which can reach 600 mV at some radiation frequencies like the one detected at 250 MHz at 3 V/m 1 KHz modulation.

However, at 20 V/m Radiation level the effect of the interference become more important and so the quantity of the additive noise for both used modulation frequencies, with more consistency of the measured additive noise for 2 Hz modulation, particularly for lower EM radiation frequencies up to 1.5 GHz for the used 2 Hz modulation and up to 620 MHz for the used 1 KHz modulation, where pick value of 1.2 V is detected at 590MHz (2 Hz modulation) and 900 mV at 250 MHz (1 KHz

modulation). This amount of additive noise is considerable comparing to the output signal amplitude of 3 V.



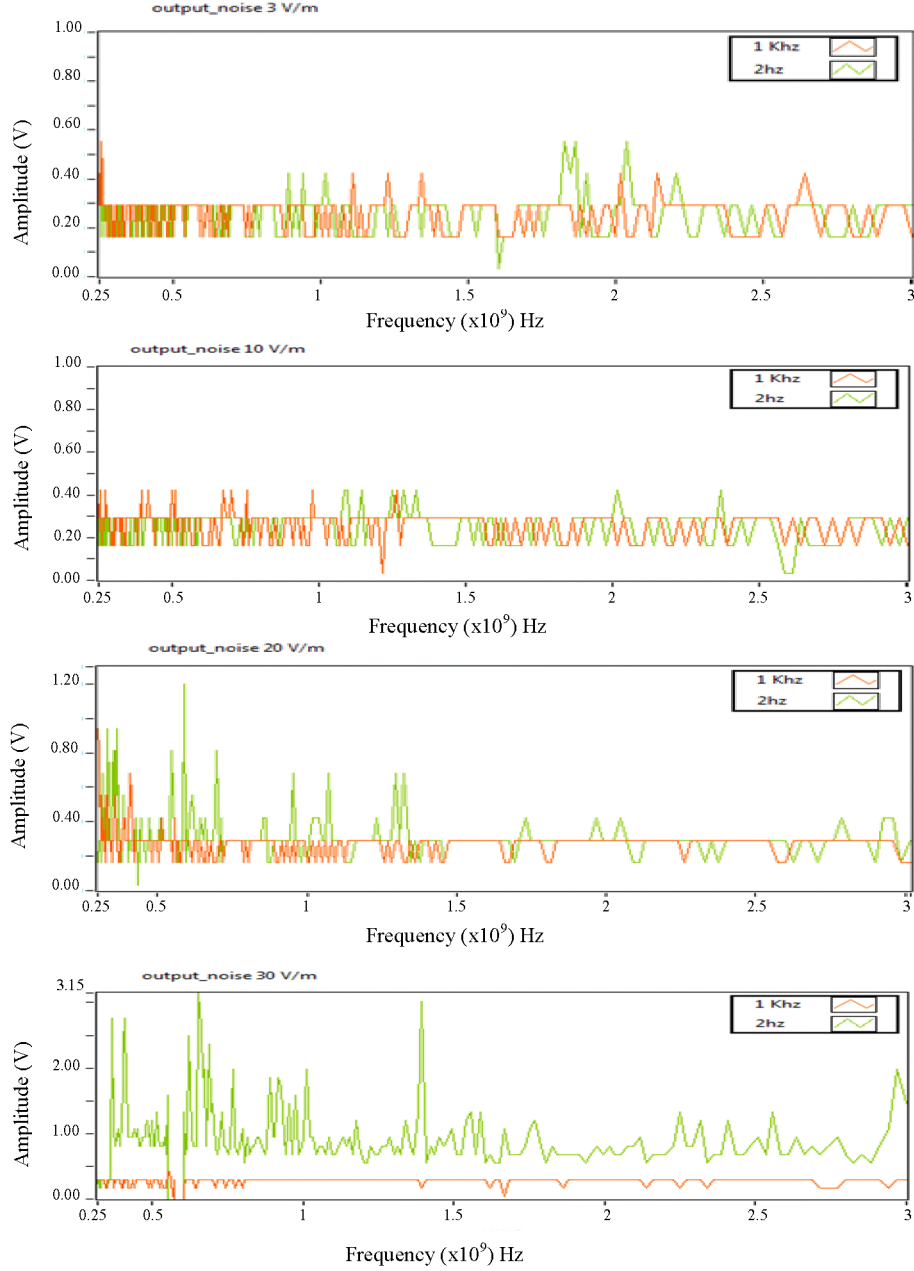***Fig.IV.19***: *The additive noise detected on the FPAA output channel at the different EM radiated energies (3, 10, 20 and 30 V/m), for the two used amplitude modulations 2 Hz and 1 KHz. This measurement is obtained using the generic ECG signal.*

Arriving to the 30 V/m radiation level, it is clear that, the additive noise for the used 2 Hz modulation become very important (average of 1 V) all over the test frequency range reaching a pick value of 3.15 V at 630 MHz radiation frequency, which is a huge amount of noise on the output channel. Moreover, with the 1 KHz modulation the additive noise remains the same level of about 300 mV all over the test frequency range except for frequencies between 582 MHz to 604 MHz, where the interference was so large to cause the FPAA to reset and the configuration to be written off so that the output was 0 V. actually, this behaviour is also observed for 2 Hz modulation, the only change here concern the first frequency causing that reset which is 562 MHz instead of the 582 MHz for 1 KHz modulation.

## VI. 2. 1. 1. 2. ACTUAL ECG SIGNAL

Using an actual noisy ECG signal, the behaviour of the additive noise on the FPAA input/output channels was quite different compared to its behaviour using the generic ECG signal.

However, this additive noise remains high on both input/output channels and is even higher since we are detecting pick values reaching 20 mV on the input (clear on Fig.IV.20), and 5 V on output as shown on Fig.IV.21.

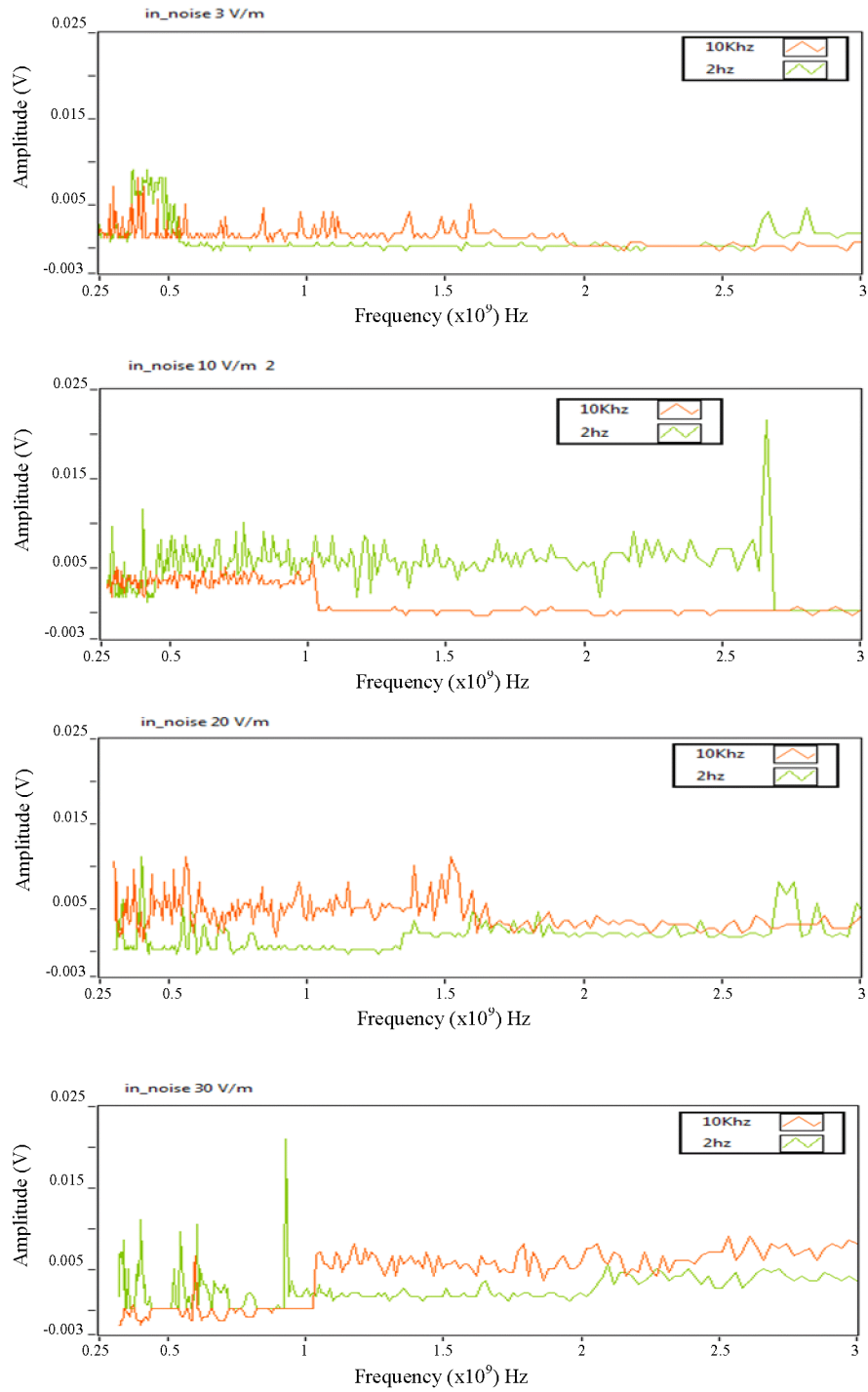***Fig.IV.20****: The additive noise detected on the FPAA input channel at the different EM radiated energies (3, 10, 20 and 30 V/m), for the two used amplitude modulations 2 Hz and 1 KHz. This measurement is obtained using the actual noisy ECG signal.*

**Fig.IV.21**: *The additive noise detected on the FPAA output channel at the different EM radiated energies (3, 10, 20 and 30 V/m), for the two used amplitude modulations 2 Hz and 1 KHz. This measurement is obtained using the actual noisy ECG signal.*
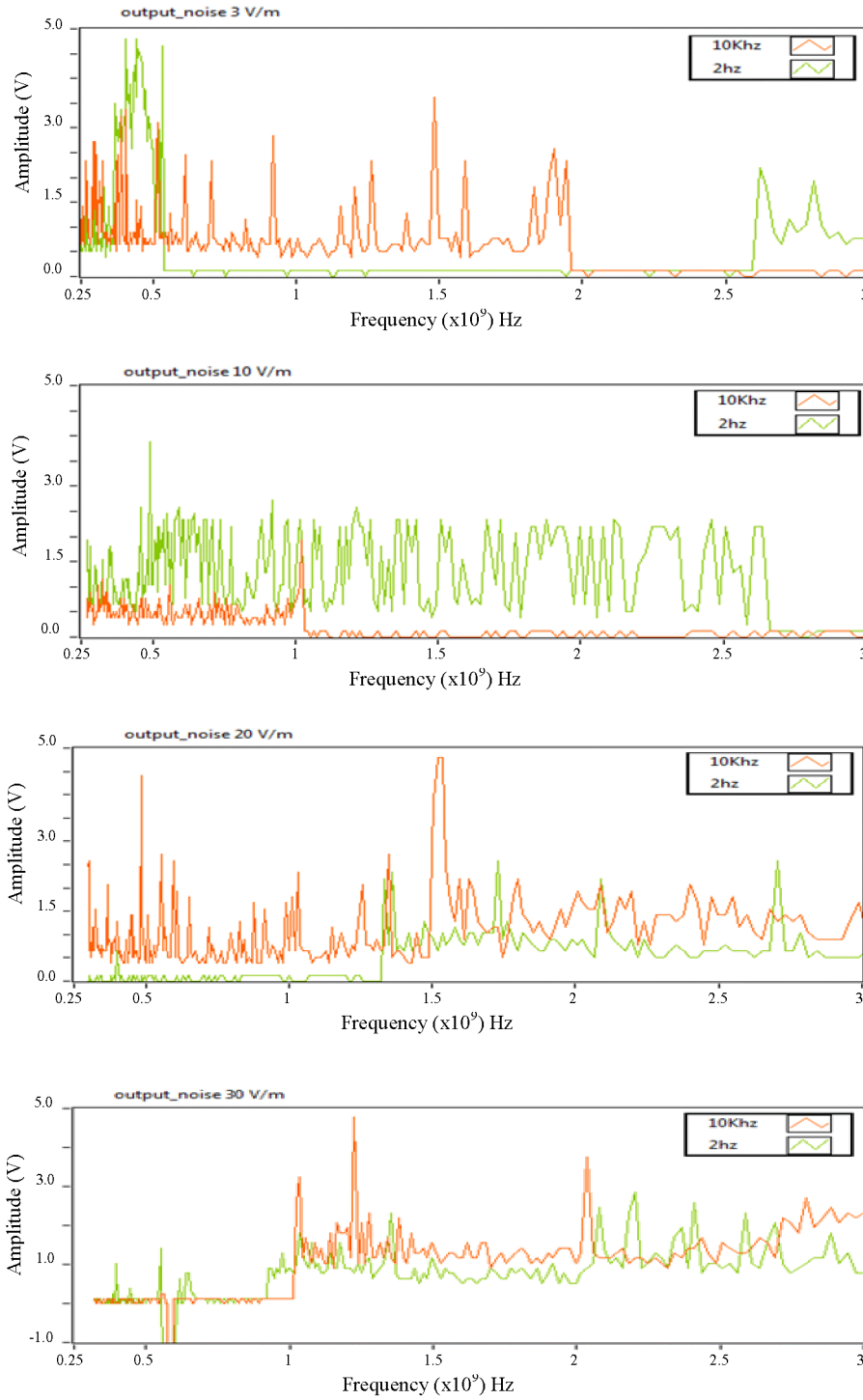
115

## VI. 2. 1. 2. The Offset

### VI. 2. 1. 2. 1. Generic ECG signal

Here the offset value to be measured correspond to the DC component that FFT analysis calculate as the amplitude of the $f_0$ component on the spectrum, it is important to remind that we are using a generic ECG signal with an offset value of 0 V,

Fig.IV.22 corresponds to the evolution of the offset through the different EM radiation amplitudes for both used amplitude-modulation 2 Hz and 1 KHz on the FPAA input channel. It is clear that even a 3 V/m radiation is generating an important offset on the used ECG signal for both used modulation frequencies. This offset increases as much as we increase the EM radiation amplitude, particularly for low disturbance frequencies from 250 MHz to 1 GHz, where lots of pick values are detected.

The highest offset values (14 mV and 12 mV) are detected for 30 V/m EM radiation at the frequency interval [562 MHz to 604 MHz] using the 2 Hz amplitude modulation, and the frequency interval [582 MHz to 604 MHz] using the 1 KHz amplitude modulation. These frequency intervals correspond actually to the highest EM radiation effect which caused a reset to the FPAA configuration, which has been already observed on the representation of the additive noise on the FPAA output channel.

Fig.IV.23 represents the evolution of the offset on the FPAA output channel for both used amplitude modulation 2 Hz and 1 KHz. According to the different representations, it is clear that the offset value on the output channel remains practically at the same level around 150 mV all over the test frequency range, for all the used EM radiated energies except for the 30 V/m radiation, where some pick values are detected at lower EM radiation frequencies. The most characteristics pick value is the 700 mV detected at [562 MHz to 604 MHz] for using 2Hz modulation and [582 MHz to 604 MHz] for using 1 KHz modulation, which correspond to the reset event.

***Fig.IV.22****: The evaluation of the offset shift on the FPAA input channel regarding the different EM radiated energies (3, 10, 20 and 30 V/m), for the two used amplitude modulations 2 Hz and 1 KHz. This measurement is obtained using the generic ECG signal.*

**Fig.IV.23**: *The evaluation of the offset shift on the FPAA output channel regarding the different EM radiated energies (3, 10, 20 and 30 V/m), for the two used amplitude modulations 2 Hz and 1 KHz. This measurement is obtained using the generic ECG signal.*

## VI. 2. 1. 2. 2. ACTUAL ECG SIGNAL

The offset behavior measured using the actual noisy ECG signal, was similar to the one measured using the generic ECG.
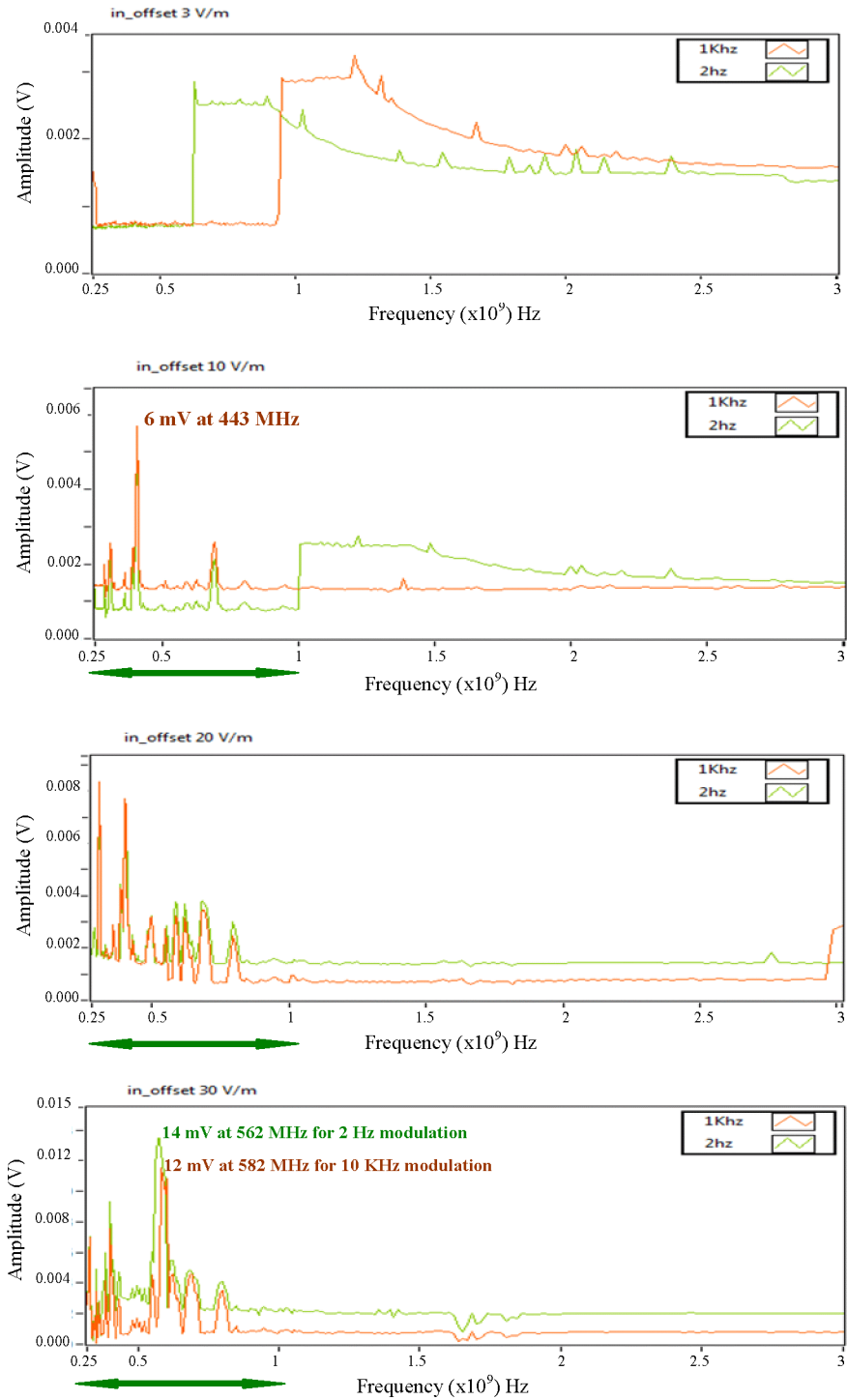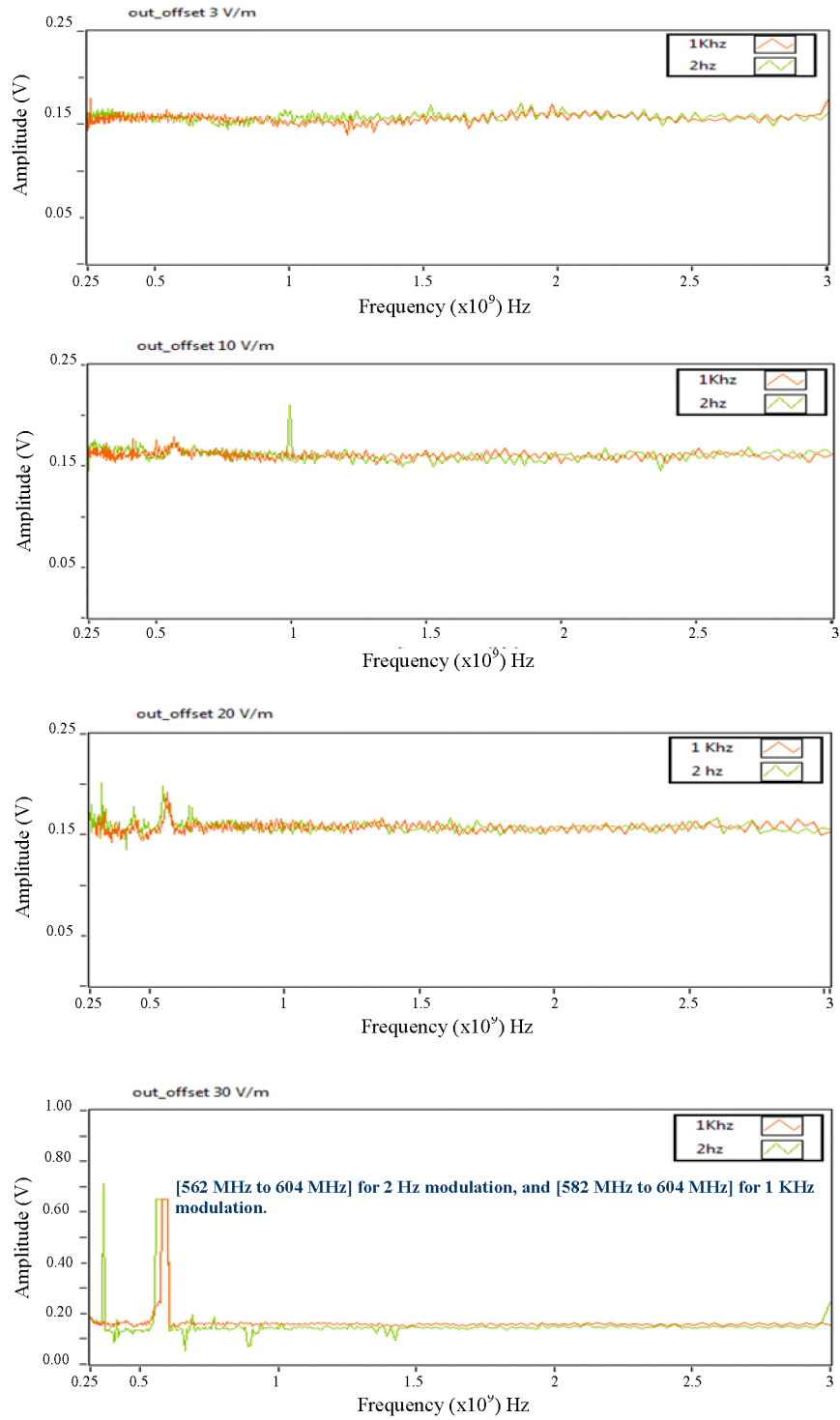


***Fig.IV.24****: The evaluation of the offset shift on the FPAA input channel regarding the different EM radiated energies (3, 10, 20 and 30 V/m), for the two used amplitude modulations 2 Hz and 1 KHz. This measurement is obtained using the actual noisy ECG signal.*
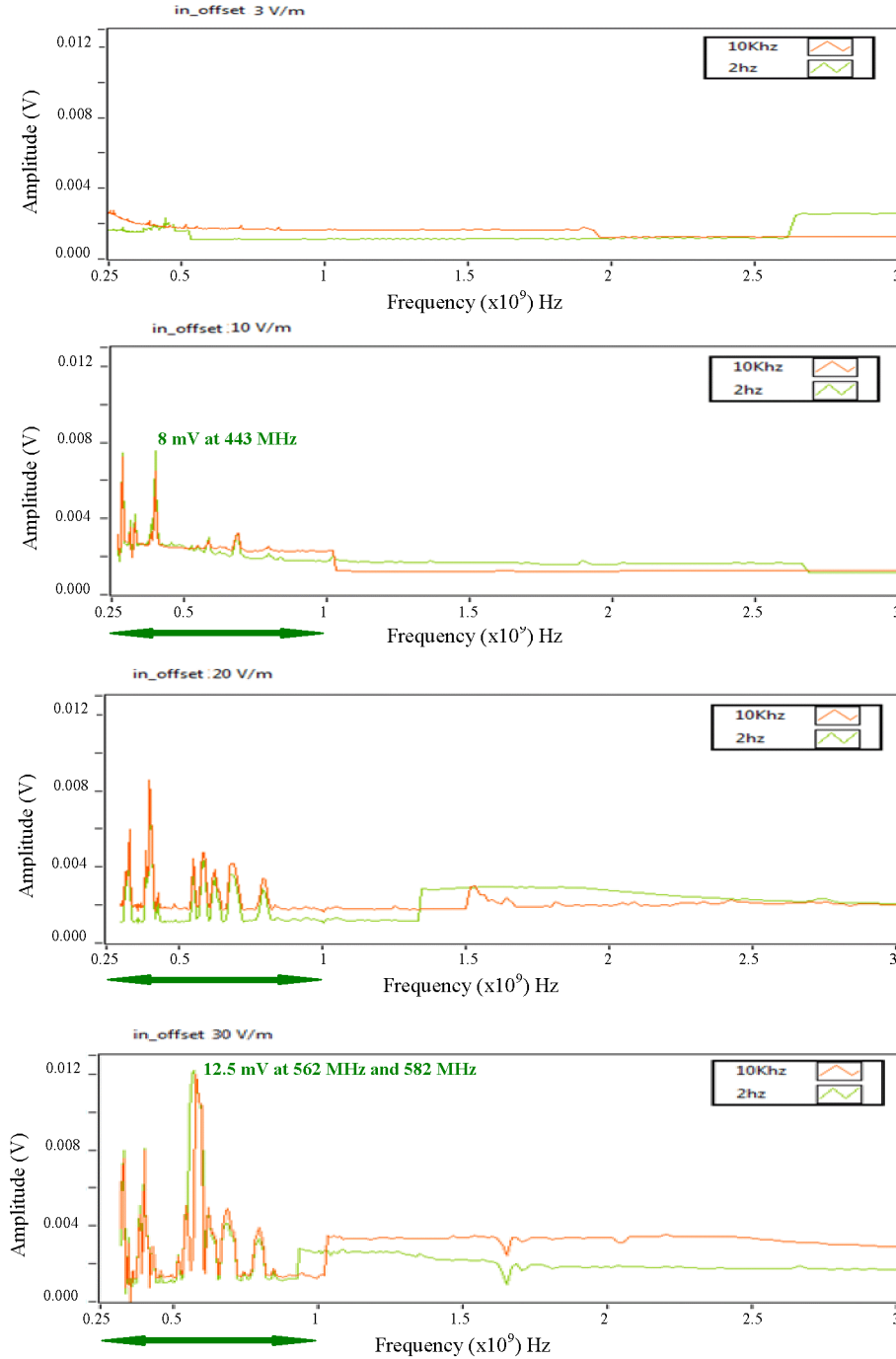
***Fig.IV.25****: The evaluation of the offset shift on the FPAA output channel regarding the different EM radiated energies (3, 10, 20 and 30 V/m), for the two used amplitude modulations 2 Hz and 1 KHz. This measurement is obtained using the actual noisy ECG signal.*
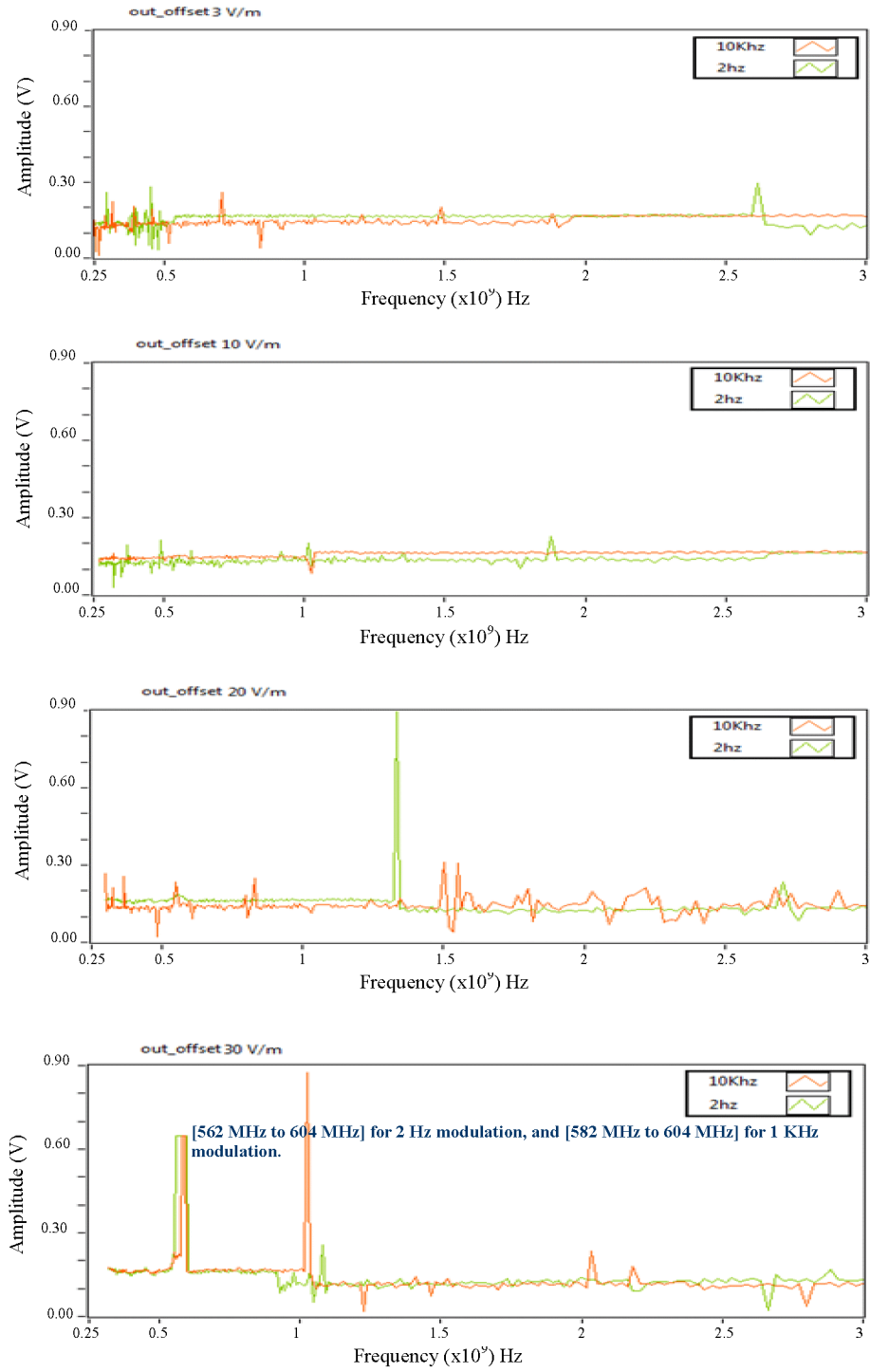
Always with an important offset value around 3 mV at 3 V/m radiation on the input channel, which increases as much as the EM radiation intensity increases, particularly within the low radiation frequencies from 250 MHz

up to 1 GHz, as shown in Fig.IV.24. In this range of frequencies we detected all the offset pick values. Here, one of the most significant pick values (12 mV) was detected at 30 V/m EM radiation within the frequency interval [562 MHz to 604 MHz] using 2 Hz modulation ([582 MHz to 604 MHz] using the 1 KHz modulation) which correspond to the reset event detected previously. Fig.IV.25 Represents the offset evolution recorded using an actual ECG signal on the FPAA output channel according to the different EM radiated energies. Similarly to the records obtained using the generic ECG signal, the offset on the output channel is remaining at the same level (between 120 mV and 150 mV) all over the test frequency range, except for some pick values which are probably caused due to the noisy nature of the used ECG signal. Here again, we can distinguish the reset event intervals at 30 V/m EM radiation.

## VI. 2. 1. 3. PHASE SHIFT AND NONLINEARITY

Performing the first test methodology, measuring the phase shift between the output and the input signals by direct lecture on the oscilloscope was always difficult because of the high level of noise.
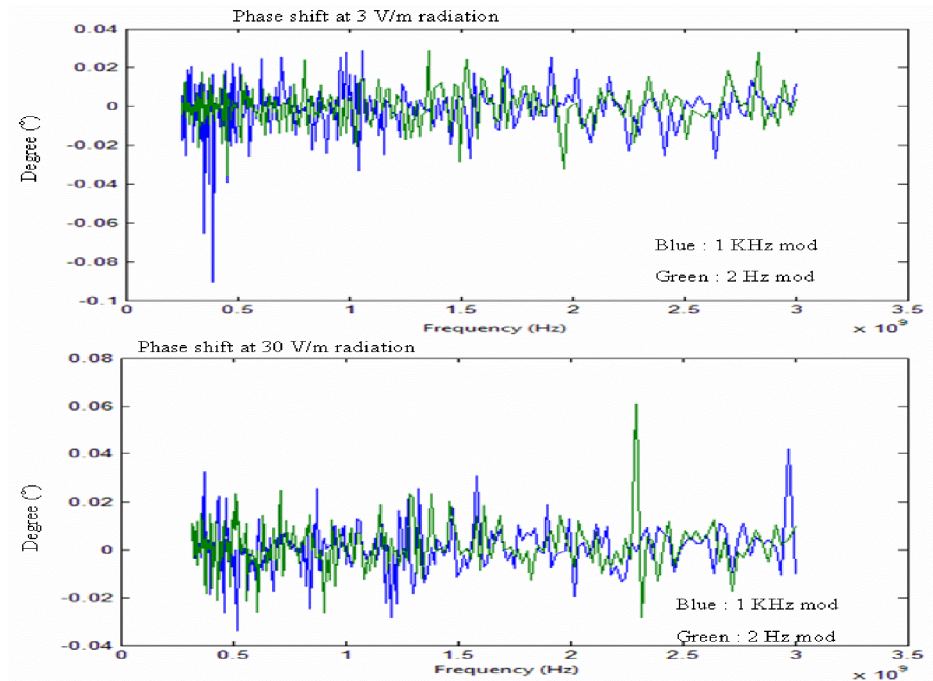


*Fig.IV.26*: The phase shift between the input and the output: a) example of 3 V/m EM radiation using the two modulation 2 Hz and 1 KHz. b) example of 30 V/m EM radiation using the two modulation 2 Hz and 1 KHz

However, using the FFT processing in performing the second test methodology, the phase shift measurement was easiest and accurate, where it was the all over the test frequency range and using the different EM radiated energies 3 V/m, 10 V/m, 20 V/m and 30 V/m stable around zero degree as shown in Fig.IV.26. a) and b).
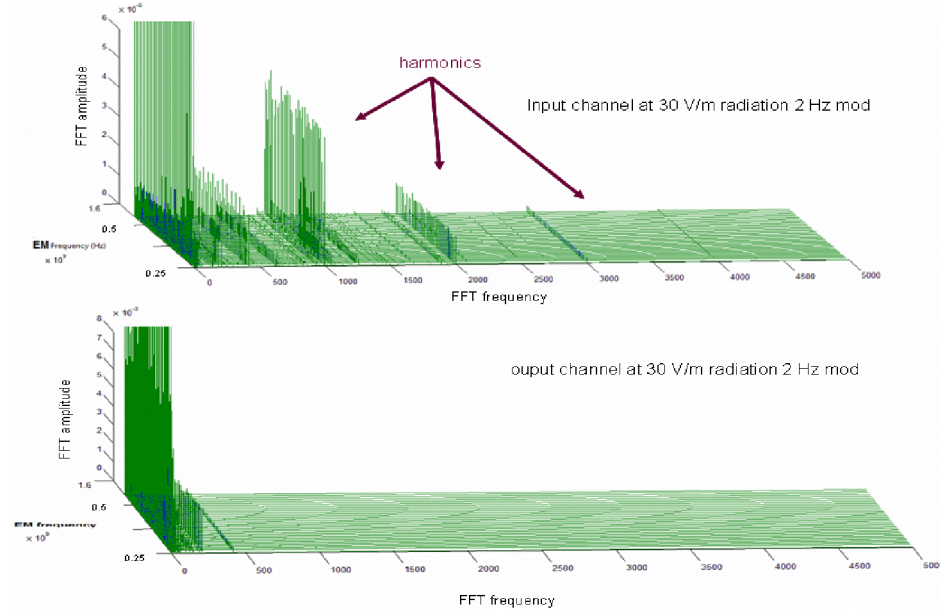


*Fig .IV.27*: *The nonlinearity behaviour of the system detected at 30 V/m EM radiation using the 2 Hz modulation on the ECG signal.*
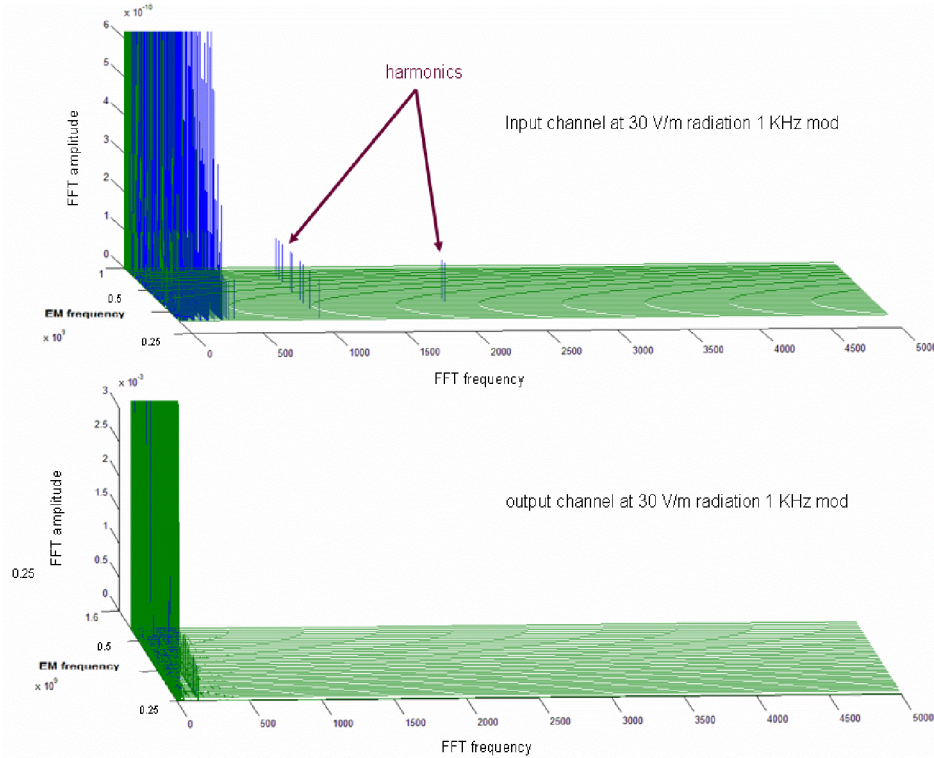


*Fig .IV.28*: *The nonlinearity behaviour of the system detected at 30 V/m EM radiation using the 10 Hz modulation on the ECG signal.*

On the other hand, the detected nonlinearity of the system function during the first test experiment at 30 V/m radiation, where using the sin wave signal, was also detected in the second test experiment at the same radiation level, where using the ECG signal (both types generic and actual). Using the 2 Hz amplitude modulation carried on the EM disturbance signal, the superposed harmonics to the useful signal, at 1 KHz, 2 KHz, and 3 KHz were present all over the test frequency range on the input channel and no one of them was present on the output channel, as shown in Fig.IV.27.

While using the 1 KHz amplitude modulation carried on the EM disturbance signal, the presence of the superposed harmonics to the useful signal at 1 KHz and 2 was actual occasional, detected for isolated EM radiation frequencies on the input channel, and doesn't exist at all on the output channel as shown in Fig.IV.28. And this is interpreted to be a kind of nonlinearity in the system function, since the response to this system supposed to be linear to a superposed group of signals at its input doesn't satisfy the linearity condition.

## VI. 2. 2. Time Domain Analysis Results

As previously mentioned, this part consists of the investigation of any eventual modifications that the EM radiation can cause to the time duration of the different parameters on ECG signal namely: P wave duration, QRS complex duration, PR interval duration, and QT (QTc) interval duration. The measurement of these different parameters was performed on the FPAA input/output signals, by mean of the NI biomedical startup kit, for the two used ECG signals (generic and actual).
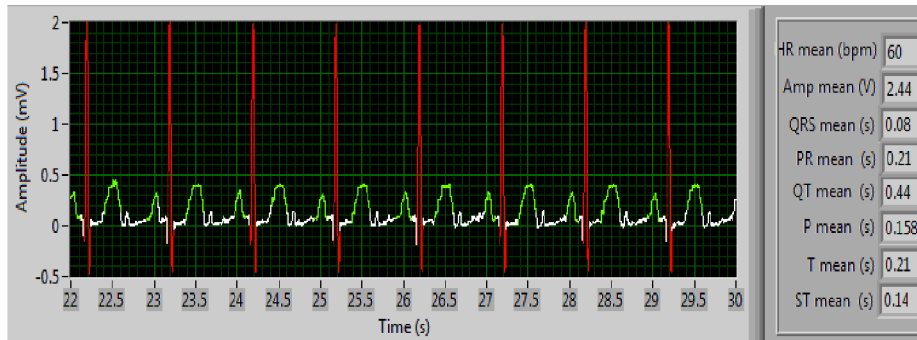


*Fig.IV.29*: *The ECG time duration parameters calculated at nominal conditions*

Actually the effect of the EM disturbance on those parameters has manifested mainly as a prolongation of the time duration or short time duration for almost all of them in both cases (using generic or actual ECG signal). However, this modification of the time duration on the different parameters was of different degrees from a parameter to another, while it was clear all over the test frequency range for all the used EM radiated energies.

Here, this FPAA configuration as an ECG signal conditioning block, targets to be used in diagnosis and monitoring systems where all decisions about the anatomical and physiological state of the heart, are in fact based on detected changes on the different waves morphology and the changes on the time duration of the different waves, intervals and segments on the recorded ECG signal. Thus, any kind of heart anomaly can be detected on the ECG record by examining morphologic and/or time duration changes.

When the change touches the time duration parameter, the electrical conduction system of the heart is concerned; these changes actually reflect a

variety of diseases depending on the affected part. In the following we will give some examples of diseases according to each graphical representation of the modification caused by the EM radiated energy on the different parts of the ECG signal.

The modifications caused by the EM disturbance we observed on the different parts of the ECG signal, were similar in both cases when we used the generic ECG signal or when we used the actual one; for both used amplitude modulation frequencies 2 Hz and 1 KHz carried on the EM radiation. It is important also here to mention that; the used ECG signal (generic or actual) at the input channel of the FPAA is a normal record which should reflect a normal heart function. Unfortunately, what we got in our measurements of the time duration of the concerned parameters (cited previously) at the output channel, was modified parameters reflecting an extensive range of possible diseases due to the influence of the EM radiation disturbance.

Another observation important to spot out on all of the following measurement representations, is the detection of the characteristic intervals where the FPAA reset event happen which correspond as previously mentioned in this chapter to [562 MHz to 604 MHz] using 2 Hz amplitude modulation and [582 MHz to 604 MHz] using the 1 KHz amplitude modulation.

## VI. 2. 2. 1. P WAVE

Fig.IV.30 and Fig.IV.31 represent the measured modification on the time duration of the P wave, on the FPAA output channel. The prolongation of the time duration of the P wave is clear for all the used EM radiated energies and for both used ECG signal and it does also show short time duration. These measurements represent actually a wrong diagnosis the fact that we are using a normal ECG signal at the FPAA input.

The prolongation of the P wave time duration can indicate in fact a fail in the atrium conduction, which consist mainly of a variety of diseases like:

✓ Left atrial enlargement disease.

✓ Diseased atrium muscles.

**Fig.IV.30**: *The detected modifications on the P wave time duration caused by the different levels of EM radiation on the FPAA output channel. These measurements concern the generic ECG signal.*

However, the short time duration of the P wave can indicate a hyperkalemia, which is actually an elevated concentration of potassium ($K^+$) in the blood

considered as medical emergency due to the risk of potentially fatal abnormal heart rhythms.
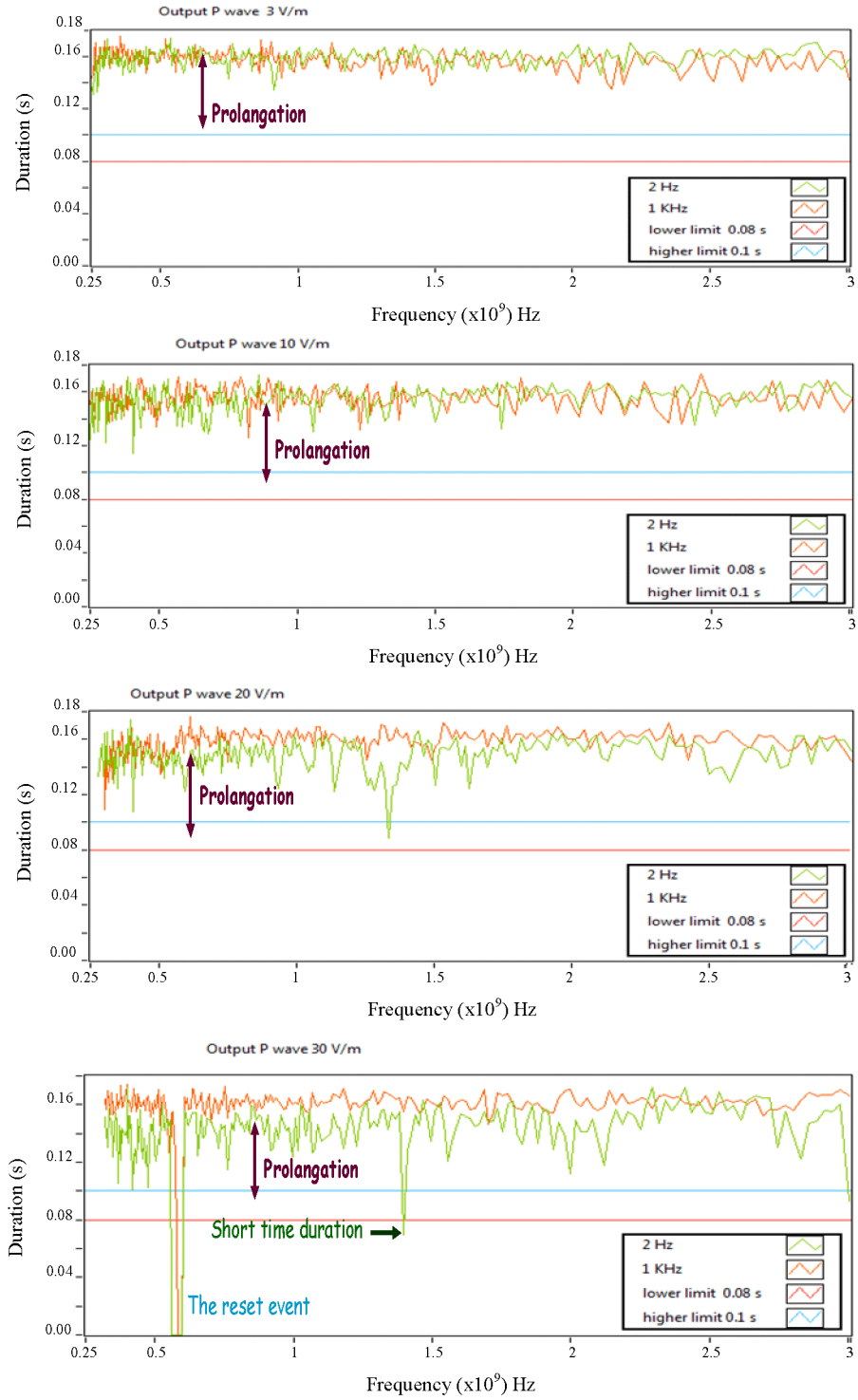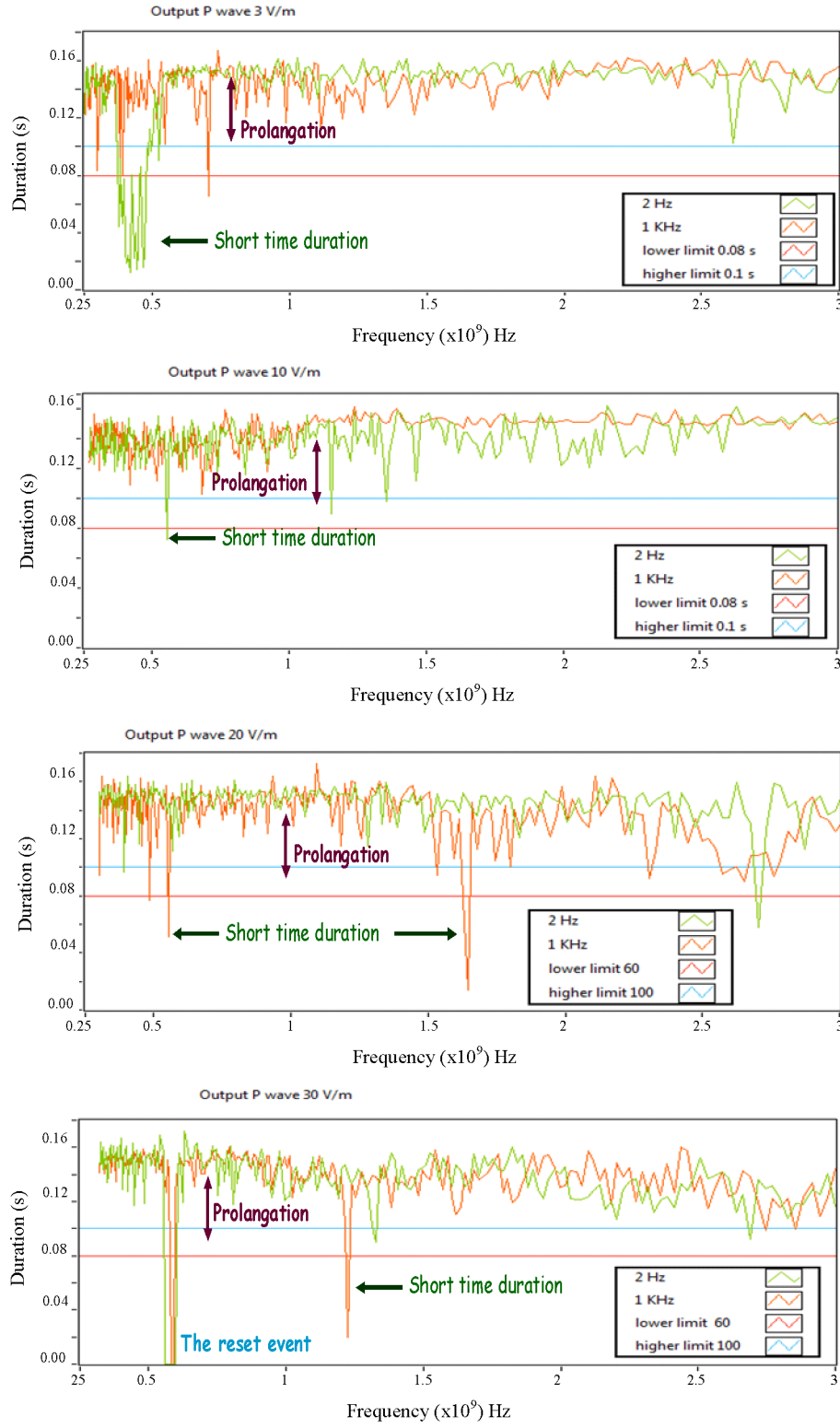


**Fig.IV.31**: *The detected modifications on the P wave time duration caused by the different levels of EM radiation on the FPAA output channel. These measurements concern the actual noisy ECG signal.*

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## VI. 2. 2. 2. PR INTERVAL

Fig.IV.32 and Fig.IV.33 represent the measured modification on the time duration of the PR interval on the FPAA output channel. This observed modification is mainly a prolongation of the time duration of the PR interval, and also some possible short time durations.

This kind of modification is generally interpreted by first-degree AV block disease: the impulse conduction from atria to ventricles through the AV node is delayed and travels slower than normal. It may also indicate Hyperaemia, acute rhumatic fever.

Like in the case of the P wave, the PR interval prolongation reflects also a fail in the electrical conduction of the heart which touch the atrio-ventricular node. However, a short PR interval may indicate Pre-excitation syndrome which is a condition where the ventricles of the heart become depolarized too early, leading to their partial premature contraction.

Here, even for this case these indications are actually wrong due to the influence of the EM disturbance, since we are always using a normal ECG signal at the input.

***Fig.IV.32***: *The detected modifications on the P R interval time duration caused by the different levels of EM radiation on the FPAA output channel. These measurements concern the generic ECG signal.*
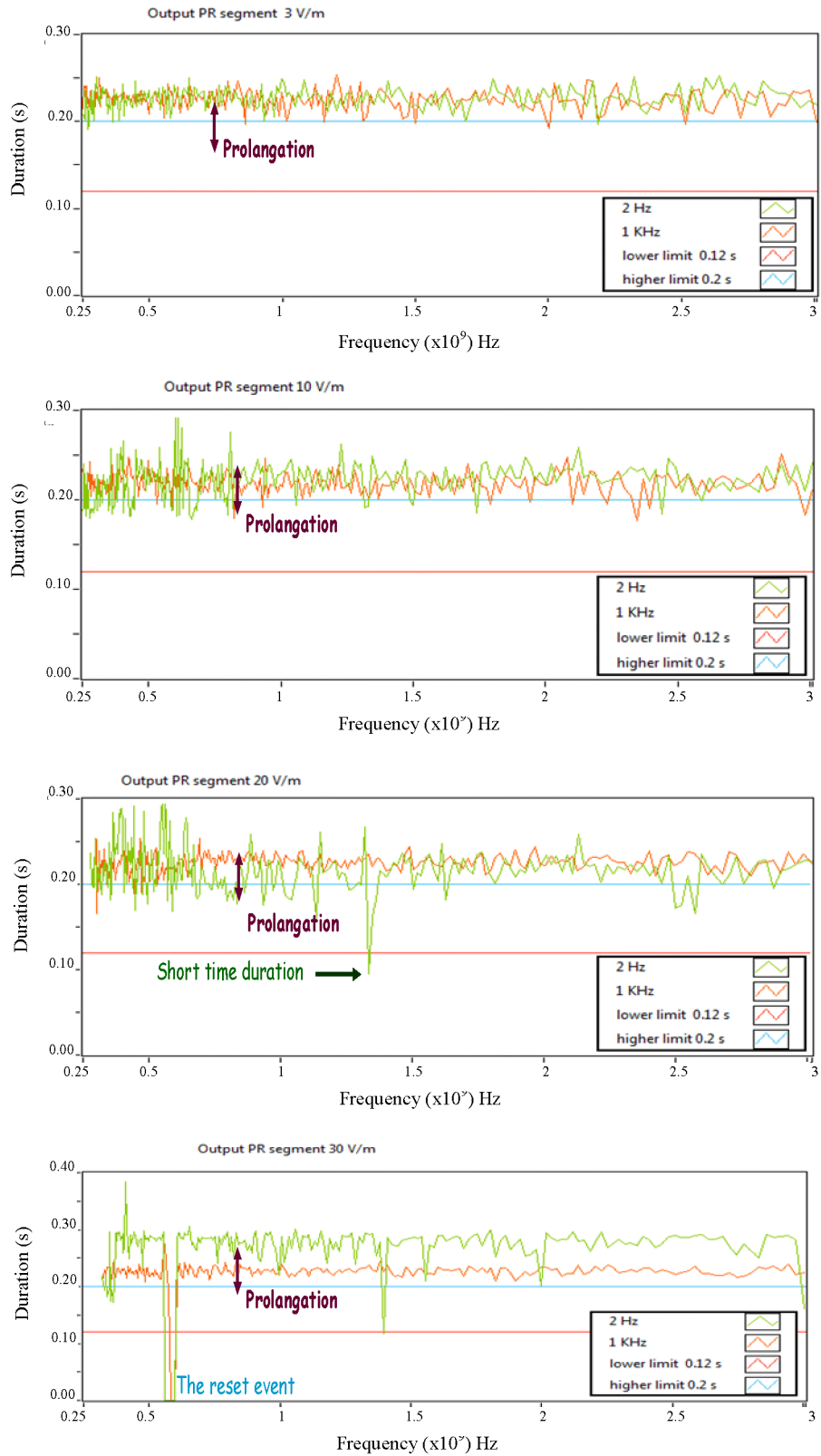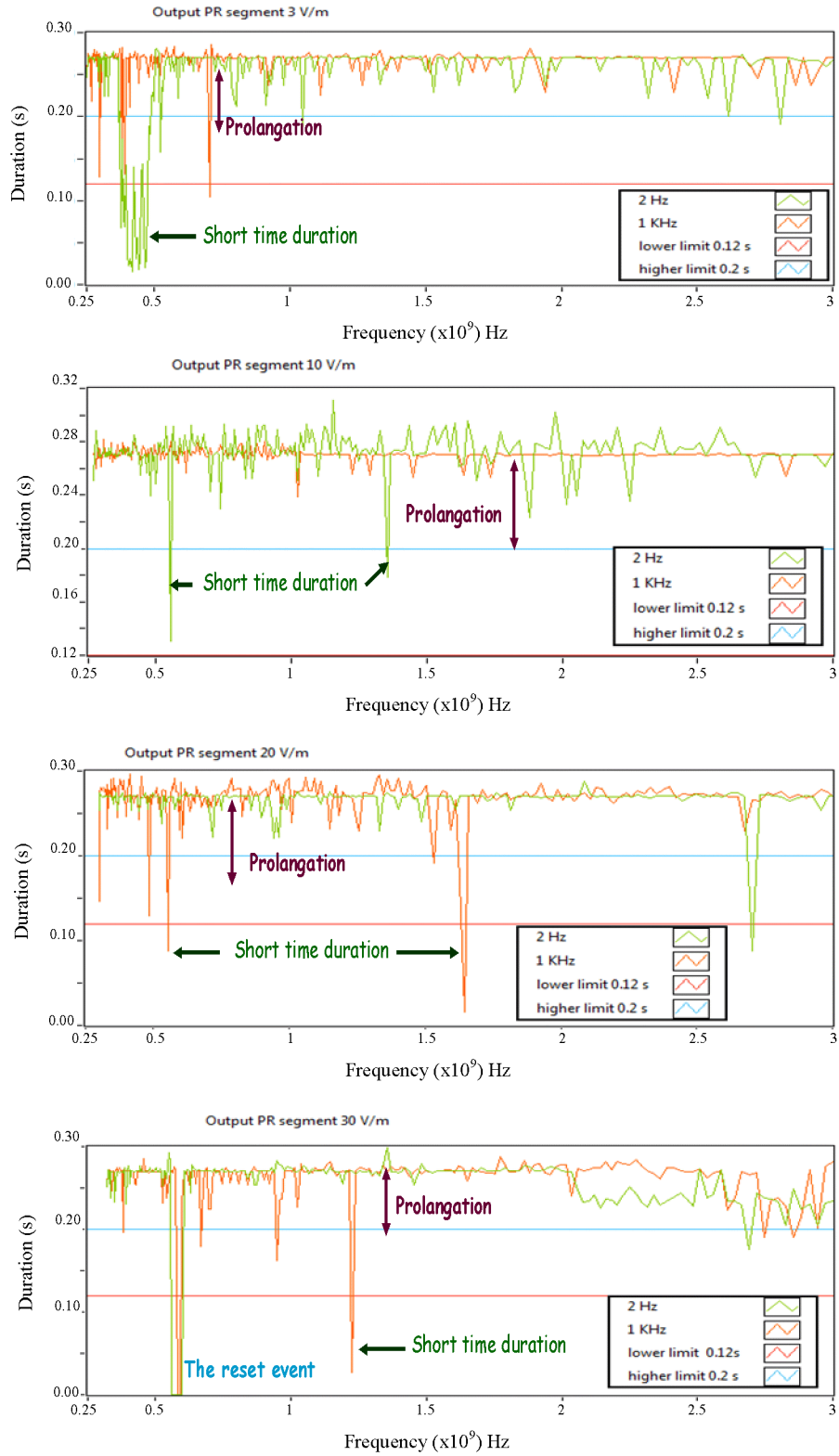
**Fig.IV.33**: *The detected modifications on the PR interval time duration caused by the different levels of EM radiation on the FPAA output channel. These measurements concern the actual noisy ECG signal.*

## VI. 2. 2. 2. QRS COMPLEX

Unlike the P wave and the PR interval, the modifications on the time duration of the QRS complex have actually different behaviour regarding the nature of the input used signal (generic or actual). Using the generic ECG signal, the QRS complex time duration seems to be immune to the EM radiation disturbance until reaching 30 V/m radiation, where it start showing some prolongations as shown on Fig.IV.34.

While using the actual noisy ECG signal, the QRS complex time duration on the output channel of the FPAA, exhibits a clear prolongation all over the test frequency range and for all the used EM radiated energies, with also some short time durations shown on Fig.IV.35.

However, the prolongation of the QRS time duration due to the influence of EM radiation may indicate:

✓ Abnormal intraventricular conduction.

✓ Block of one of the bundle brunches.

✓ Ventricular arrhythmia (bradycardia).

In case of QRS complex short time duration may indicate:

✓ Ventricular arrhythmia(sinus tachycardia).

✓ Hypertrophia

✓ Myocardial infraction.

***Fig.IV.34***: *The effect of the different levels of EM radiation on the QRS complex time duration, at the FPAA output channel. These measurements concern the generic ECG signal.*

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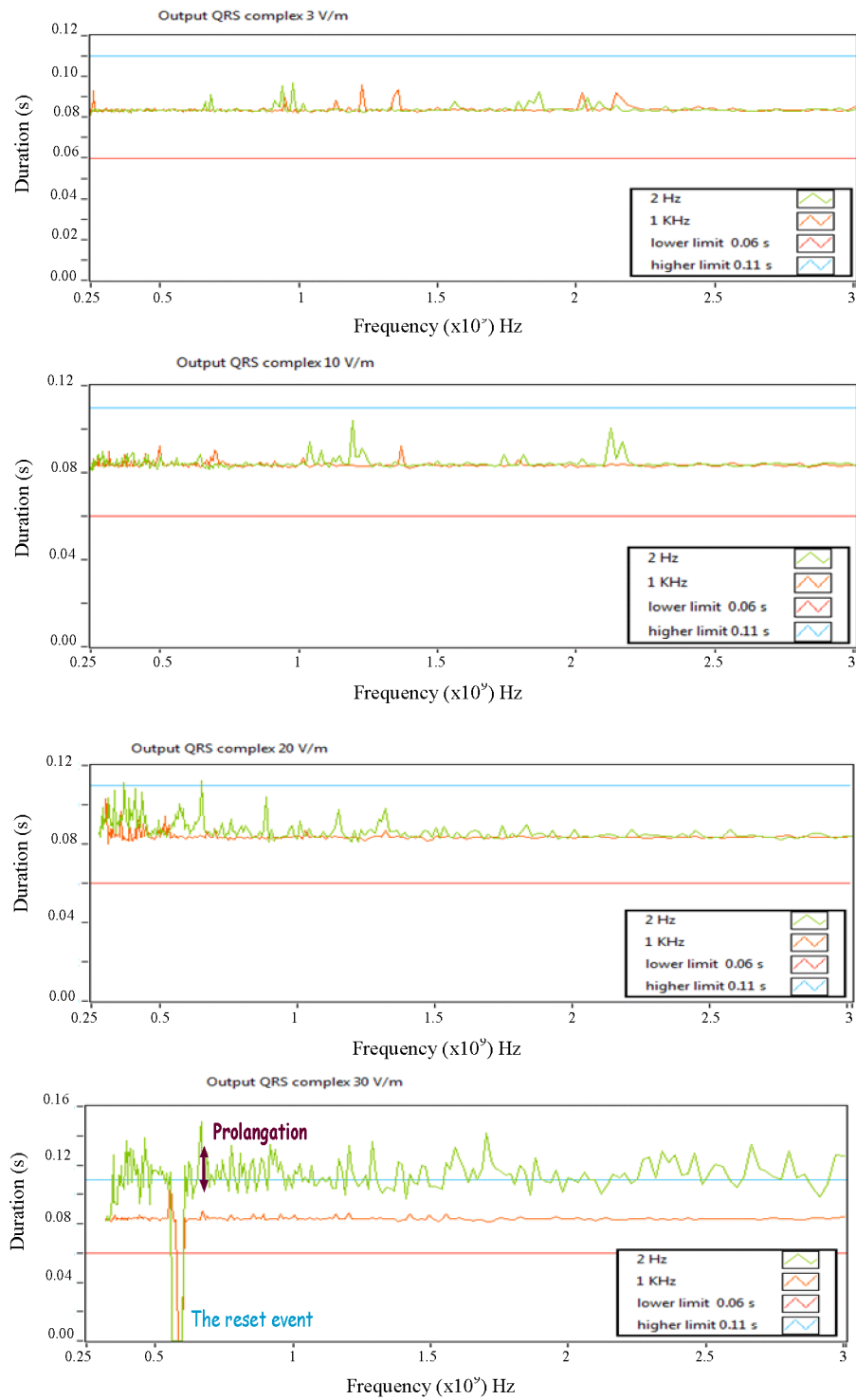
**Fig.IV.35**: *The effect of the different levels of EM radiation on the QRS complex time duration, at the FPAA output channel. These measurements concern the generic ECG signal.*
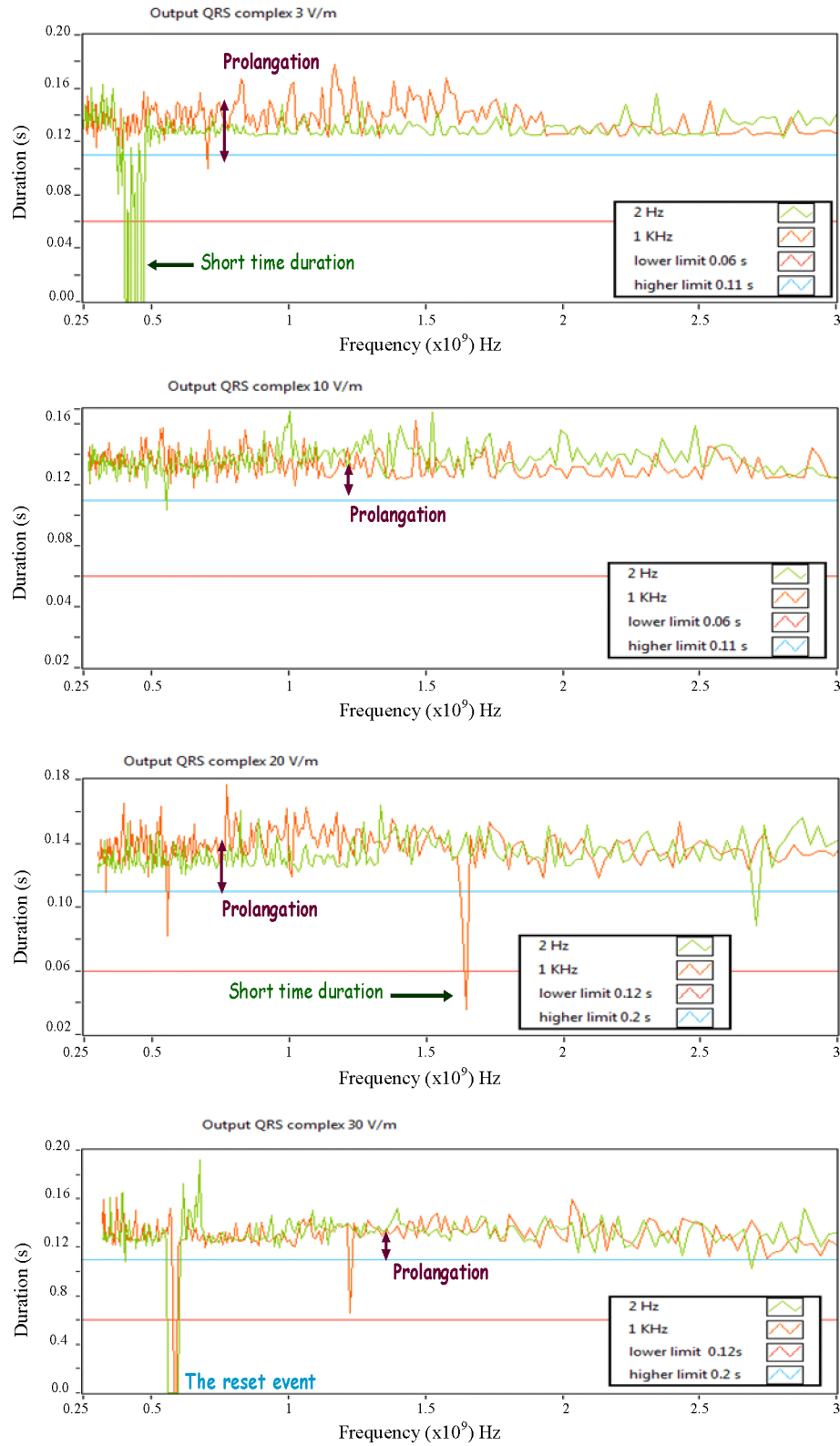
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## VI. 2. 2. 4. QT (QTC) Interval

Fig.IV.36 and Fig.IV.37 represent the measured modifications on the time duration of the QT (QTc) interval on the FPAA output channel, caused by the EM radiation. This modification is mainly a prolongation of the QT (QTc) interval time duration using both ECG signals (generic and actual).

The QT (QTc) interval represents electrical depolarization and repolarization of the left and right ventricles. A lengthened QT (QTc) interval is a biomarker for ventricular tachyarrhythmia and a risk factor for sudden death. A prolongation of the QT (QTc) interval may indicate:

- ✓ Heart failure.

- ✓ Ischemic diseases.

- ✓ Electrolyte disorder.

- ✓ Myocardial Infarction

While a short QT (QTc) time duration may indicate:

- ✓ Early repolarisation.

- ✓ Genetic disorder associated with sudden death.

- ✓ Hypercalcemia.

- ✓ Hyperkalemia.

**Fig.IV.36**: *The detected modifications on the QT (QTc) interval time duration caused by the different levels of EM radiation on the FPAA output channel. These measurements concern the generic ECG signal.*
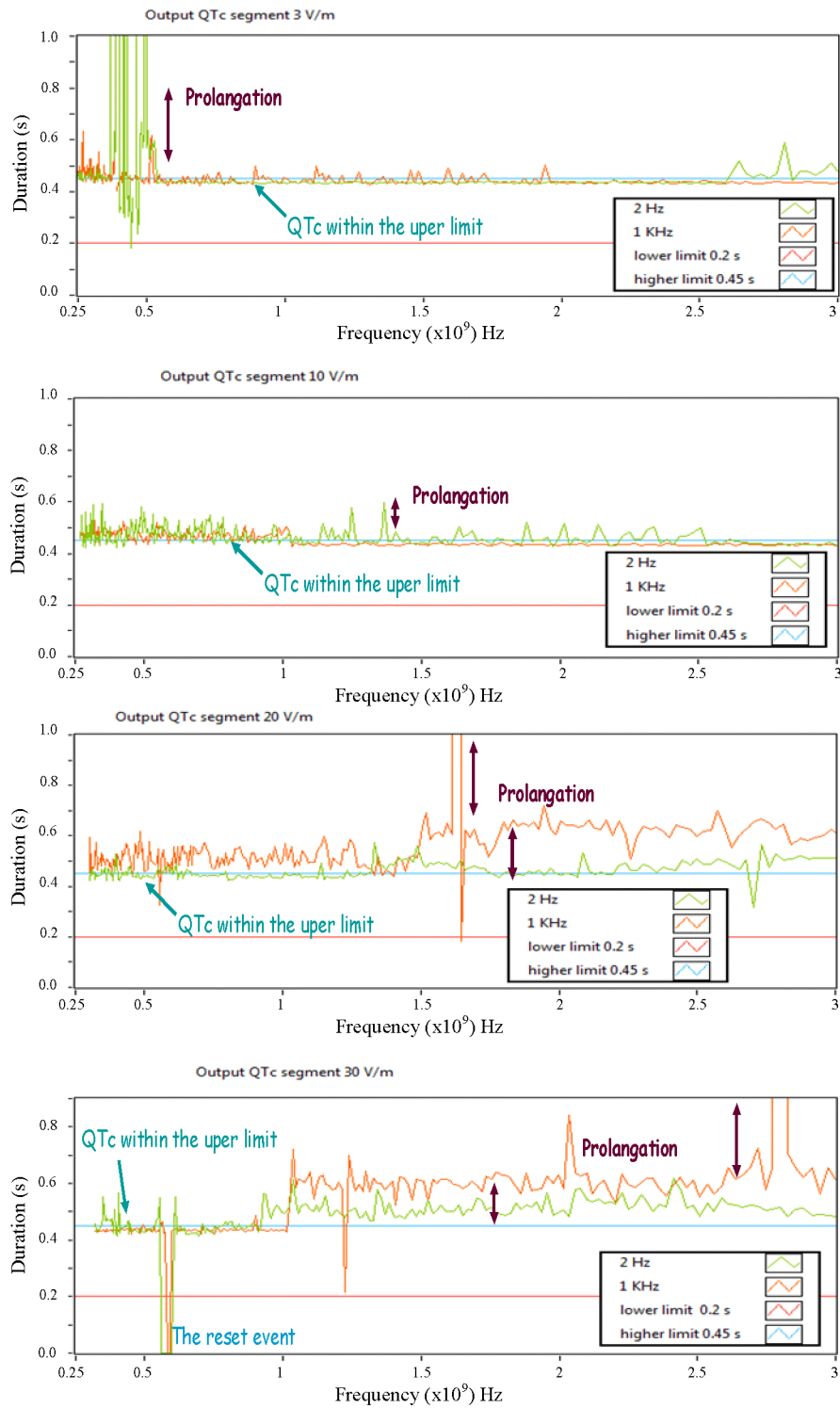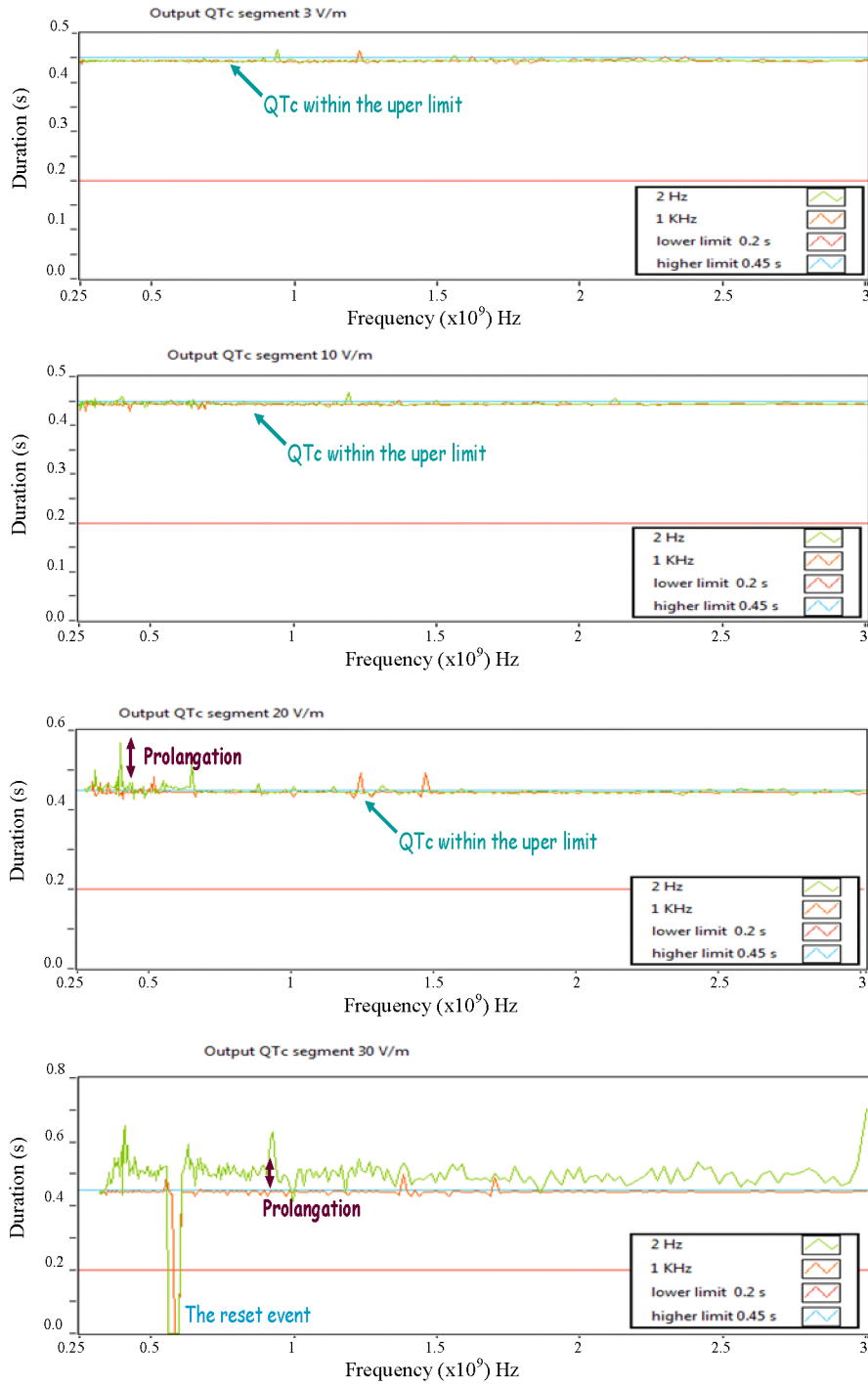
***Fig.IV.37***: *The detected modifications on the QT (QTc) interval time duration caused by the different levels of EM radiation on the FPAA output channel. These measurements concern the actual noisy ECG signal.*

## VII. IMPORTANT REMARKS AND RECOMMENDATIONS

Going through the different parts in this experimental study, where the assessment of the immunity behaviour of the FPAA based biomedical application devices to EM radiation, was performed based on two different methodologies in evaluating the effect of different EM radiations on the FPAA function; lot of remarks concerning the differences between the two applied methods are important to spot out and some recommendations should be taken in account for more reliable and accurate immunity measurement test for such critical applications.

### VII. 1. REMARKS

By examining the evaluation of the EM radiation effect on the FPAA input/output channels on the different obtained measurements, the most intuitive remark to be cited is the difference in the system behaviour regarding the use of a sin wave signal or an ECG signal. This difference concern:

   ✓ The totally different additive noise behaviour obtained in the two methods of measurement, which can be observed each used EM radiation. In particular, this difference is more important when detecting the characteristic frequencies where the Reset event happens at 30 V/m EM radiation on the FPAA output channel. Using a sin wave input signal the reset event happens within the frequency interval [252 MHz to 282 MHz], while it happens within the frequency interval [562 MHz to 604 MHz] using a 2 Hz amplitude modulation ([582 MHz to 604 MHz] using 1 KHz amplitude modulation) using the ECG signal. This reset event represents the worst EM radiation effect on the FPAA function.

   ✓ The offset shift on the FPAA input/output channels was undetectable using the first test method except for using an EM radiation of 30 V/m which was very high compared to the 3 mVpp input signal. While it was important offset shift, clearly detectable using the ECG as the input signal even for the lowest EM radiated energies (3 V/m and 10 V/m).

✓ The nonlinearity behaviour detected in the FPAA function observed in the first test measurement is also observed in the second test but is more present using the 2 Hz amplitude modulation than its presence using the 1 KHz amplitude modulation, and that for both ECG signals (generic and actual)

Using the ECG signal in this kind of tests doesn't only make the measurements realistic and appropriate to the application, but it reduces spectacularly the test measurement time. Thus, from some days to some hours for the whole test frequency range at each EM radiated energy.

Evaluating the immunity level of the FPAA to EM radiation by observing the evaluation the additive noise and the offset on the FPAA input/output channels wasn't enough. Since, at this part of frequency response analysis, the FPAA seems to be functioning with just a presence of an additive noise and an offset shift of the input/output signals. However, an investigation of the effect of the disturbance on the ECG signal time parameters was necessary to compliment and batter inform about the functionality state of the FPAA circuit, where the measurements revealed the important modifications that EM radiation can cause to these parameters (in particular when using an actual noisy ECG signal), and which can lead to a wrong diagnosis.

The behaviour of the additive noise was random and unpredictable when we used the actual noisy ECG signal compared to its behaviour using the Generic one, except for the detection of the reset event frequency coordinates, which were the same for both cases. Actually, the additive nose was more important and very high using the actual ECG signal even for lower EM radiated disturbance.

It is important to cite that in term of offset shift, the higher EM radiation effect was detected at the lower immunity test frequencies in the range between 250 MHz to 1 GHz.

The measurements of the different ECG time parameters have presented similar behaviour regarding the use of the generic and the actual ECG signal, with exactly the same reset event frequency coordinates: [562 MHz

to 604 MHz] for the use of 2 Hz amplitude modulation and [582 MHz to 604 MHz] for the used 1 KHz amplitude modulation.

## VII. 2. RECOMMENDATIONS

According to the cited remarks we stress on the following recommendation in order to perform a reliable and accurate immunity test for such applications:

- ✓ It is clearly batter to use the ECG signal in such kind of immunity test.

- ✓ Taking direct measurements in such test is not all the time possible and reliable; thus, it is preferable to employ processing means such as FFT to get more accurate measurements.

- ✓ Give a particular attention to the lower test frequencies (lower to 1 GHz).

- ✓ Perform the test using different amplitude modulations carried on the EM radiation.

- ✓ In case of testing biomedical devices for immunity purposes, taking in account all the aspects and parameters of the target biologic signal should be taken in account for more global information.

## VIII. Bibliography

[1] D.P.Morales et all, "Flexible ECG acquisition system based on analog and digital reconfigurable devices", Elsevier Sensors and Actuators A: Physical journal, 165(2011), pp: 261-270. 2010.

[2] http://www.anadigm.com/

[3] ANSI/AAMI EC38:2007; Medical electrical equipment – Part 2-47: Particular requirements for the safety, including essential performance, of ambulatory electrocardiography systems. 2007.

[4] Aldo Baccigalupi , Annalisa Liccardo , Nicola Pasquino;" *A methodology for testing immunity of field programmable analog arrays to radiated electromagnetic field";* Elsevier Journal of the International Measurement Confederation (IMEKO); ISSN: 0263-2241, Volume 44, Issue 10, Pages 2165–2174. December 2011.

[5] EN 61000-4-3:2006, Electromagnetic compatibility (EMC) – Part 4-3: Testing and measurement techniques, electromagnetic filed immunity test.

[6] EN 61000-4-20:2003, Electromagnetic compatibility (EMC) – Part 4-20: Testing and measurement techniques – Emission and immunity testing in transverse electromagnetic (TEM) waveguides.

[7] A. Bayés de Luna, "Basic Electrocardiography: NORMAL AND ABNORMAL ECG PATTERNS", 2007, ISBN: 978-1-4051-7570-8.

[8] http://www.physionet.org/physiobank/database/mitdb/

[9] https://decibel.ni.com/content/docs/DOC-12646

# GENERAL CONCLUSION

# CONCLUSION AND PERSPECTIVES

The main objective of this experimental study was to assess the immunity of a Field Programmable Analog Array FPAA-based biomedical devices concerned by the ECG signal to Electromagnetic radiated disturbance, in order to contribute into the improvement of the existing Electromagnetic Compatibility (EMC) standards, and the development of new and more customized standards. The idea here was not to verify if the FPAA is working or not in the presence of an external EM disturbance, so that we can attribute the binary stat "1" to the FPAA working under influence of the EM radiation, and attribute the binary stat "0" the FPAA not working under the influence of EM radiation. But the idea was: in case of the presence of an external EM radiated disturbance, is the working FPAA reliable? Is it functioning correctly regarding the expected output? How deeply can the EM radiation influence the FPAA function? What kind of distortion can the EM radiation cause to the treated signal? And what are the aspects that the effect of the EM radiated energy on the FPAA function exhibit?

After performing the different steps of the immunity test experiment, getting measurements, and analysing them, some concluding points are to consider:

✓ According to the detected additive noise and the offset shift on the FPAA input/output channels, to the possible nonlinear behaviour in the FPAA function, and the different detected modifications, that the EM radiation had caused to the different time parameters of the normal ECG signal. It is formal to confirm that: under the influence of EM disturbance, the use of the FPAA circuit in such biomedical devices is not totally safe, unless it should be enclosed in specific shielding proper to this kind off critical applications.

✓ The actual experiment has shown that using the sinusoidal signal to mimic the ECG signal behaviour in this type of immunity test was not a relevant choice, since the test measurements showed totally different results regarding the use of a sine wave signal or an ECG signal.

✓ Actually using the ECG signal in this immunity test didn't only made the test more realistic, but it also reduced spectacularly the measurement time from few days using sine wave signal to few hours using the ECG signal ( for one whole immunity level test). Here the use of the ECG signal doesn't make any difficulties to the test process since lot of categories of ECG signal are available for free download on the web site of the MIT-BIH database, and even it is possible here to connect the FPAA input to a patient via the electrodes for a short time measurement.

✓ When testing such biomedical devices for immunity to EM disturbance purposes, all the aspects and all parameters concerning the target biologic signal should be taken into account (shape and morphology and also the signal time parameters). Since in this experiment, the factor confirming the non total immunity of the FPAA to EM radiation was the different modifications detected on the different time parameters of the ECG signal, while looking to the other parameters, the FPAA seemed to be immune with just the presence of some distortions on the treated signal.

Based on the test obtained results and the important remarks derived from this study, some further research studies can be proposed in order to pursue the actual work:

✓ This experimental study can be extended to explore in depth the possible changes on the different ECG waves morphology due to the presence of the EM radiation on the FPAA, where any morphology changes is characteristic in the diagnosis of distinguishable disease.

✓ It will be very interesting to study and investigate deeply the coupling problems inside the FPAA circuit under exposition to an EM disturbance, in order to better understand the origin of the additive noise on the signal and its random behaviour regarding the different used signals. It may also explain the nonlinearity in this system behaviour.

✓ Like the case of the ECG signal, this study can be extended to study the immunity of the FPAA circuit as part of different biomedical applications concerning other types of signal as EEG, EMG and others, which are actually weaker signals than ECG.