Magnetic interference from a tramway in electrocardiogram signals

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1 Abstract

ECG is a method used in diagnostics and monitoring of the heart. The ECG measures the electrical activity between two or more predetermined positions on the body surface. These ECG signals might be disturbed by surrounding magnetic fields, which might induce an interference into the signals. A tram passing by an ECG equipment has the possibility to induce interference into the ECG signals, due to changing currents on the tram line.

In this study experimental and real life measurements have been made to analyse whether or not a tram track passing by Skåne University Hospital, Lund, would interfere destructively with ECG signals. Experiments were made to simulate an accelerating/decelerating tram, contact loss between pantograph and overhead caternary and AC ripple of the DC current powering the tram network. Experimental simulations were made representing the magnetic field of these interfering sources at distances 10 meters and 25 meters, respectively. The real life measurements were made in Göteborg at Slottsparken, where the equipment was placed at an approximate distance of 10meters and 25meters from the tram track, respectively.

All measurements were made with both a monitor and an oscilloscope since the monitor has a filter that removes some of the signals which were to be investigated. Measurement showed that AC Ripple of the DC current interfere with ECG signals. In the case of ripple the interference is larger measured with an oscilloscope than the monitor. The ripple due to a 6 pulse rectification showed quite large interference. For a 12 pulse rectification the interference was reduced considerably. At a distance of 10 meters the ripple interference was large, though the interference was greatly reduced at a distance of 25 meters. In Göteborg a 6 pulse rectification of the current is used and quite large interference could be seen correlate with passing trams at a distance of 10 meters, though not all passing trams showed any disturbance in the ECG signals. For measurements at 25 meters no noticeable interference could be seen correlate with passing trams. Acceleration and deceleration showed no interference for any measurements. Contact loss between pantograph and overhead caternary showed only an interference in the experimental simulations without filter. No cases of contact loss could be seen when measuring in Göteborg and therefore no measurements for this in a real life setup could be recorded.

A passing tram will induce interfering disturbances into ECG signals. Whether if the interference will be of a problem in interpretation of ECG signals is a question that experienced physicians has to answer.

Contents

2 Introduction

2.1 Background

The ECG is a widely used technique to investigate the heart for diseases. Registration of the ECG can be achieved over limited periods of time or used to monitor a patient's health during their hospital stay. ECG registers the electrical signal from the heart at specific positions on the body surface. The ECG wires will enclose a surface area, where magnetic fields might induce interference. In Lund there is a desire to build a tramway, which will operate between Lund C and Science Village/ESS and pass by Skåne University hospital, Lund.[1] Both Skånes university hospital and Lunds commun would be benefited by an investigation of how a future tramway could disturb ECG measurements.
A tram runs on direct current with a small ripple of alternating current. Whether this current will induce interference in ECG signals enough to risk patient safety was of concern for the hospital, therefore a theoretical investigation was performed by Dick Van Bekkum, a consultant specializing in Electrical rail systems.[2] The investigations showed some potential cases of disturbance of ECG signals, which might be large enough to disturb an ECG measurement. Trams might create a large enough field to interfere with ECG signals when they accelerate/decelerate, lose contact with the overhead wire and from the AC ripple in the DC current. As these potential areas exists, the hospital decided it was of importance to do an experimental investigation, which this master thesis has focused on.

2.2 Purpose

To experimentally investigate whether and how a future tram track passing by the hospital might affect ECG signals.

2.3 Aim

ECG signals might be affected by the magnetic field generated by the current on the caternary and tram lines of a tram track, and when the passing tram draws power or looses contact with the overhead contact wire. The aim of this thesis is through experimental measurements and in real life measurements determine how large these interferences will be and how they will affect the ECG signals.

2.4 Objective

Experimentally simulate interference for distances of 10m (IT/MT department) and 25m (Main buildings of hospital) for 300Hz ripple, 600Hz ripple, acceleration/deceleration tram and contact loss between over head caternary.
Measure in real life the interference from passing tram of distances of 10m and 25m.

2.5 Methodology

This thesis has experimentally investigated the potential interference sources from the tram, which are alternating current ripple from the rectification of AC to DC current, acceleration/deceleration and break of current between pantograph and overhead current wire.[2] Since it is the magnetic field from these changes in current which induces interfering currents into the ECG, the magnetic field for these situations has been experimentally simulated. Simulations have been made by the use of an electromagnet, ECG simulator, monitor and other relevant electrical equipment. A worst case scenario for the area enclosed by the ECG wires will be used, where the area will be maximized. Real life measurements have been made by the tram track at Slottsskogen, Göteborg. Here the ECG simulator and ECG monitor were placed at distances 10m and 25m from the tram track to investigate how the magnetic field from the tram might affect the ECG for various layouts of wire configuration and orientation.

3 Theory

3.1 Electrocardiography, ECG

The heart's electrical activity can be measured by placing leads on specific positions on the body. These leads measure the total electrical potential produced by the muscle cells in the heart as it contracts. The ECG curve represents how the electrical potential spreads throughout the heart during a heartbeat.[3]

3.2 Action potential

During a heartbeat the heart creates an electric field which can be registered as an ECG signal. Each heart cell creates a small electrical field as it contracts, where the sum of all these electrical signals creates the signal known as the ECG.

Each cell has a membrane potential, which is a difference in electrical potential between the inside and outside of the cell. The potential is maintained at a certain level by leak channels and ion pumps in the cell membrane. When a signal is sent through the body the cell's potential changes, by opening or closing the channels and pumps. For some cells an action potential is used to depolarize the cell. An action potential depolarizes the cell to its maximum when the stimuli exceeds the threshold for depolarization, below the threshold no polarization can occur.Heart cells are depolarized through action potentials, though they always have a leakage of ions through the membrane to become more and more positive so as to reach this threshold and spontaneously fire an action potential. When the heart cells in the Sinusoidal node reaches their threshold a heartbeat is initiated. Depolarization by an action potential occurs quickly and changes the potentials of the membrane. As maximum depolarization occurs, repolarization begins and the cell returns to its normal state. During repolarization no new action potentials can be fired. ECG measures how this depolarization and repolarization travels throughout the heart.[4]

3.3 The heart

The hearts main purpose is to supply the body with oxygen enriched blood. The heart consists of two halves, were each half contains an atrium and ventricle, the atrium receives the blood and the ventricle pumps the blood. The departments of the heart is divided by the myocardium, the hearts wall, which consists of muscle cells. These muscle cells are contracted at different times during the heart beat as the electrical pulse travels through the heart. The blood flow are controlled by valves to ensure a blood flow in the right direction throughout the heart.[4]

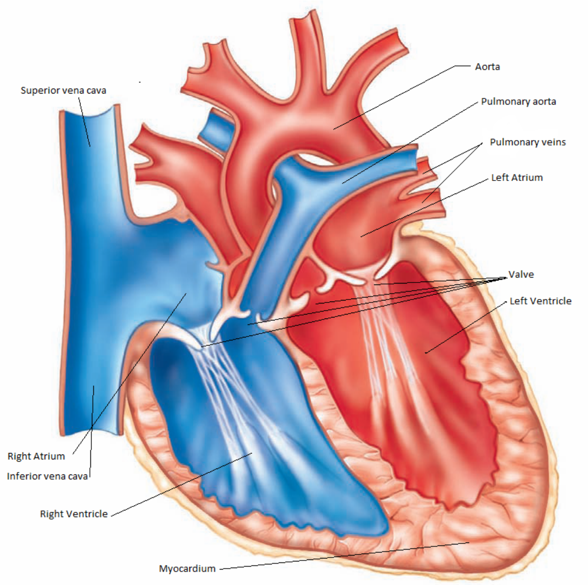


Figure 1: The anatomy of the heart. [4]

3.4 The heartbeat

The heartbeat is initiated by a spontaneous firing of an electrical impulse in the sinusoidal node (SA node). The impulse changes the potential of the muscle cells membrane from -90mV to about 20mV. A spontaneous firing are possible due to the SA nodes cells having a resting potential which slowly depolarizes until polarization reaches the threshold for the action potential. This slow depolarization is called a pacemaker potential. As the cells reach the threshold for the depolarization the heart will contract, and during repolarization the heart will relax. As described earlier repolarization will forbid any new signals to be transmitted until the cells are totally repolarized, which is the reason for a maximum pulse rate.

From the SA node the electrical signal travels to the atriums which contract simultaneously, hereafter the signals arrive at the atrioventricular node, where the signal will be collected and delayed. The delay ensure that the atriums and ventricles does not contract simultaneously. From the AV node the signal travels to the ventricles via the bundle of His and reaches the ventricles via the bundle branches, where it depolarizes the myocardium. The transport of the signal throughout the heart, hence the depolarization of the heart, makes the heart contract and is called systole. The relaxation of the heart is called diastole which occurs as the cells repolarizes. During systole blood will be ejected and during diastole the heart is filled with new blood. Should the SA node for some reason not fire electrical signals on a regular basis, other cells of the heart also contains pacemaker potentials, such as the AV node, however the firing rate is lower than the one for the SA node.

During depolarization a dipole field is created from the heart cells. The total dipole field from all cells, represent the general direction of the hearts electrical potential. The potential varies over time depending on which phase, systole or diastole, the heartbeat currently possess. As different parts of the heart becomes depolarized it can be registered as an ECG signal on the body surface. As the cells repolarize the dipole field will have an opposite polarity from the depolarization.[4]

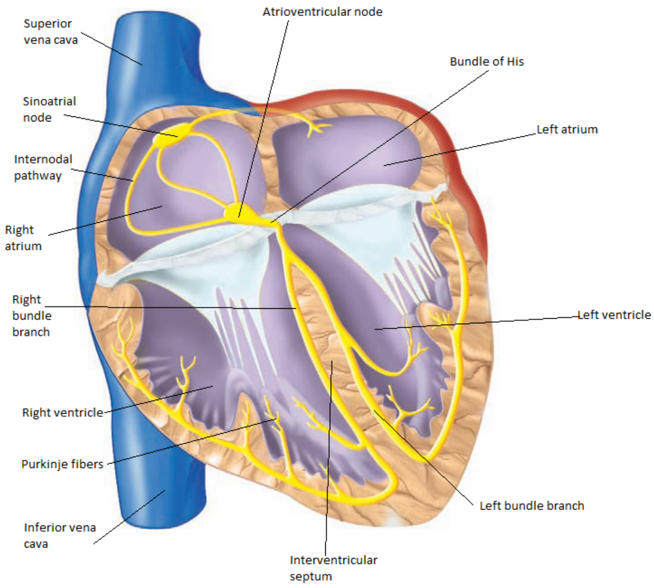


Figure 2: The electrical activity of the heart.[4]

3.5 ECG-curve

The ECG curve represents the repolarization and depolarization of the atriums and ventricles. The curve can be divided into intervals, where the heart is in a constant state during the flat intervals of the curve. The P-wave shows the depolarization of the atriums, the QRS- complex shows the depolarization of the ventricles and the T-wave shows repolarization of the ventricles. Repolarization of the atriums is covered by the QRS complex.

An ECG curve has signals in the order of 0.5-4mV, with frequencies between 0.01-250Hz. ECG equipment can register signals from 10μV to 1mV with frequencies between 0.1 to 200Hz, where new equipment can register signals as high as 500Hz. A problem with measuring ECG is that the signals can be affected and distorted by the electrodes, other muscle contractions and the skin onto which they are placed.[3] [4] [5]

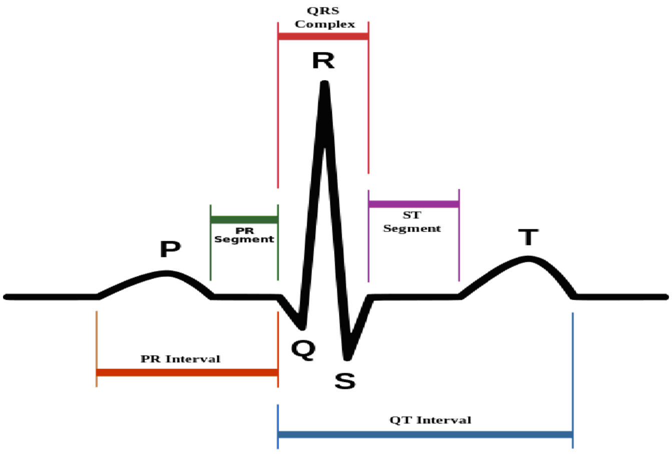


Figure 3: The ECG curve.[6]

3.6 High frequency ECG

ECG signals are usually registered between 0-150Hz, though higher frequencies exist in ECG signals. The QRS complex are the one which provides the highest frequencies in a high frequency ECG measurement. An analysis of signals above 150Hz can be made to investigate whether or not features of higher frequencies are of diagnostic value. Registration of higher frequencies requires better resolution in both time and amplitude as High frequnecy-QRS signals has amplitudes in the order of μV, and therefore also requires low noise levels. High frequency ECG might register frequencies as high as 1000Hz, though the most common case is to investigate the signal in the frequency band between 150-250Hz. [7]

3.7 ECG Interpretation

Interpretation of ECG is based on different aspects of the ECG curve. The frequency of the heartbeat, the different waves and the behaviour of the intervals between can indicate a decease in the heart. Different deceases changes the ECG curves in specific ways. One decease that can occur in the heart is atrial fibrillation, where a small ripple of up to 400waves/minutes can be seen between each QRS complex and the ventricles has an irregular rhythm. Another problem is when the heart skips heartbeats, why a pacemaker can be used to initiate the missing heartbeats. A pacemaker which initiates a heartbeat is shown as a peak in the ECG curve. These are only two deceases that changes the ECG curve, though a lot of other changes in the ECG curve can be seen when investigating the heart. [8]

3.8 Leads

The ECG curve is registered by placing the electrodes at specific positions on the chest and limbs. These different configurations are called leads.

3.8.1 Bipolar limb leads (I,II,III)

These leads are measured between different limbs (Fig. 4). The lead shows the potential difference between the two limbs that are connected. Due to varying potentials during a heart beat in both limbs the theoretical interpretation are complicated. These leads are measured between the two arms (I), between the left leg and the right arm (II), and the left leg and the left arm (III). The amplitude of one of the leads can be calculated from the other two.[5]

$$II = V_{LA} - V_{RA} \quad (1)$$

$$II = V_{LL} - V_{RA} \quad (2)$$

$$II = V_{LL} - V_{LA} \quad (3)$$

3.8.2 Unipolar limb leads (aVR,aVL,aVF)

For these leads the voltage potentials of the leads are registered in relation to a constant potential, constant during the whole heartbeat. The interpretation of these signals are easier since these leads are compared to a constant potential. The reference potential is in practice established by combining two of the leads, with same sized resistances, and measure the desired signal in comparison to these (Fig. 4). These leads are registered using the same configuration as for the Bipolar leads. However here the aVR lead is the difference between the right arm and the two interconnected leads, aVL the left arm and the interconnected leads and aVF the left foot and the interconnected leads.[5]

$$aVR = V_{RA} - \frac{V_{LA} + V_{LL}}{2} \tag{4}$$

$$aVL = V_{LA} - \frac{V_{RA} + V_{LL}}{2} \tag{5}$$

$$aVF = V_{LL} - \frac{V_{LA} + V_{RA}}{2} \tag{6}$$

3.8.3 Unipolar precordial leads (V1,... V6)

Leads placed on the chest measures more accurate signals. These leads are placed in predetermined positions (Fig. 4), so as to always get the same measurement. To achieve a constant voltage lead, the left arm, right arm and left leg are bound together with three equal resistances. The leads are measured between one electrode and the constant voltage.

These 12 leads gives the 12-lead ECG, where the limb leads are the ones most prone to pick up noise. This is due to them being furthest away from the heart, where signals from the muscles on the way may distort the ECG.[5]

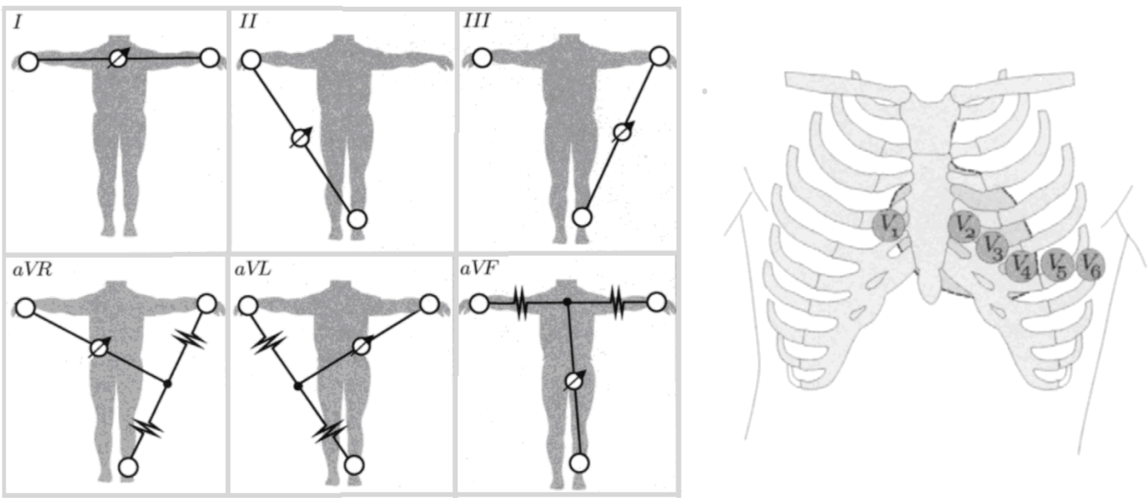


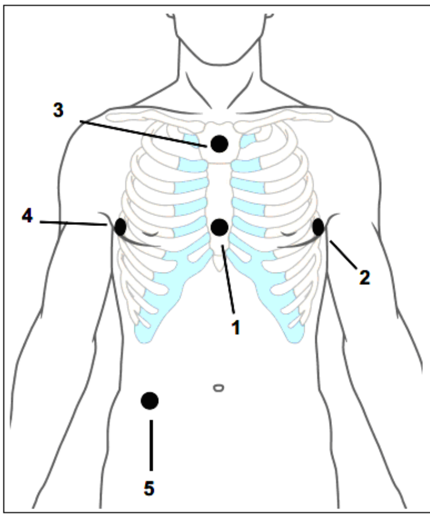
Figure 4: The ECG leads and the electrodes placements. [3]

3.8.4 EASI-leads

EASI leads calculate the 12-lead ECG from only five electrodes placed on the patient (Fig. 5). In this configuration one electrode is the ground and can be placed anywhere on the patient, the four remaining are placed on the lower sternum (E), left midaxillary line (A), right midaxillary line (I) upper sternum (S). The EASI registers three leads, A-I which gives a horizontal vector, E-S gives a vertical vector, and A-S gives an anterior-posterior vector. From these leads the 12-leads can then be calculated.

$$L_h = a(A - I) + b(E - S) + c(A - S)2 \tag{7}$$

In the equation a, b and c are determined to give the best agreement with the 12-ECG. EASI leads differs only slightly from the real 12-lead measurement.[9]



EASI Electrode Placement		
1	E (V)	on the lower sternum at the level of the fifth intercostal space
2	A (LL)	on the left midaxillary line at the same level as the E electrode
3	S (LA)	on the upper sternum
4	I (RA)	on the right midaxillary line at the same level as the E electrode
5	N	reference electrode - can be anywhere, usually below the sixth rib on the right hip

Figure 5: Placement of the EASI electrodes. [10]

3.9 Tram systems

The tramway which are planned to be built in Lund will be powered by a DC current of up to 1200A and a voltage of 750V. The system is design so that there can be drawn a maximum current of 3200A, when multiple trams are traveling along that section of the tramway. The current which will propel the trams will have to be rectified and/or transformed from 10kV AC to the 750V DC in a rectifying station before supplying the tram network. To power the tram, the current is guided from the overhead caternary to the pantograph, through the motor of the tram and down to the rails.

A magnetic field will be induced when the power line is fed with current. The constant field from a DC current would not create any magnetic interference on the ECG, as static fields don't induce a current. However the DC current on the line will vary somewhat due to ripple from the rectification. Swedish standards for creating a tram network, prescribe the overhead caternary to be placed 5-6 meters above the rail, where the ideal case in Lund would be 5.5meters. In Göteborg trams are powered by a voltage of 600-750V DC current and use 1200-1500A as they run on the line. The maximum current on the track is around 3000A. Rectification for the current in Göteborg is done through a 6-pulse rectifier, thereby creating a ripple of 300Hz, with harmonics. Four different models of trams are used in Göteborg, M28, M29, M31 and M32. The model M28 have a motor with the capacity of 4×44kW and were built in the sixties, whereas M29 are driven by 4×50kW and were built in the beginning of the seventies. The model M31 which have a 300kW motor were built in the eighties and nineties. The newest model M32 which is produced still has been used since 2004 and has a motor of 4×106kW. For these models, the models M28 and M29 looks very similar and are sometime connected together, thus creating a tram containing both models . The number series used for each model are, numbers 701-770 for M28, 801-860 for M29, 300-305 and 307-208 for M31 and 401-465 for M32.[2] [11] [12] [13] [14] [15]

3.9.1 Interference in ECG from tram

The current in the tram system will be the source of interference for ECG signals, where the possible sources of interference are AC-ripple of the DC current, acceleration and deceleration, and current break. The magnetic field created due to these current changes will be able to induce an interference into an area enclosed by ECG wires, Fig. 6 .

A source will be able to interfere with another victim source if the victim conductor is susceptible to the emission from the source conductor. Couplings between source and victim occur when energy is transferred between them, which can happen due to electric, magnetic or electromagnetic fields irradiated from the source. These fields are created from currents traveling through a conductor. Magnetic and electric fields will be affected by the wave impedance, Z, which is a ratio between the electric and magnetic field. This ratio determines how fields couples to a conducting structure. In the far field this ratio is constant since the electric and magnetic field decay at the same rate. They are also orthogonal to each other and the wave propagation in the far field, creating a so called plane wave. However in the near field when $d < \frac{\lambda}{2\pi}$, where $\lambda = \frac{c}{f}$ and d=distance,λ=wavelength, f= frequency and c=the speed of light in vacuum, the interference is determined by the source characteristics. The dominant field of the magnetic and electric depends if the field is created by a high change in voltage or current, where current change gives a magnetic field and a voltage change gives an electric field. For a loop the main field which will be created will be a low impedance magnetic field.

Knowledge on the coupling between victim and source is important, since reduction in interference depends on the reduction of the coupling factor. This will also help in determine how to shield the interference. For a tramway the main source of interference is magnetic, as the created fields will be mainly due to large changes in current. The fields which will affect the ECG in the hospital are in the near field. [2] [16]

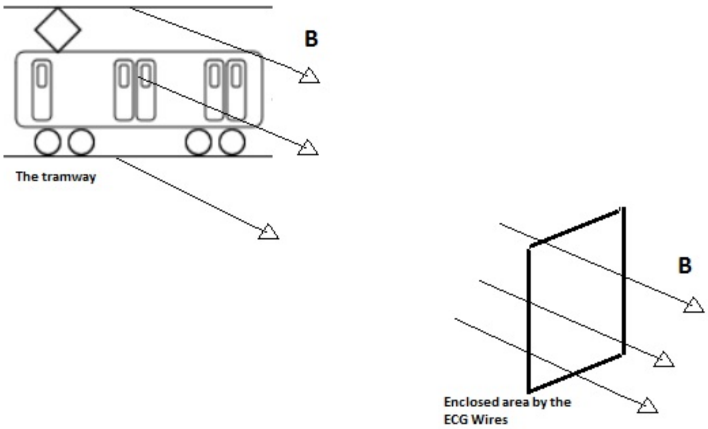


Figure 6: A tram traveling on a tramway creating a magnetic field that induces an interference into the ECG signals, due the field that travels trough the enclosed area.

3.10 Magnetic fields

When an current is flowing through a conductor a magnetic field will be produced. The magnetic field from an alternating current has the ability to induce a voltage into a victim circuit, which might lead to a disturbances of the signals in the victim conductor. The interference is induced when the magnetic field travels through an enclosed area of the victim loop, where a larger area will result in higher induced voltage and therefore more interference. An area which is totally perpendicular to the magnetic field results in most of the magnetic field passing through the loop, why a larger inductance is achieved than for a victim loop which is not perpendicular.The induced voltage can be described by Eq. 8, where M describes the mutual inductance between the two conductors. It is clear that a rapid current change induces a large voltage, while a slow change induces less voltage. The mutual inductance is dependent on areas of the loops for the victim and source, their orientation, the distance between them and magnetic screening in-between.

In the Eq. 8, V_N describes the induced voltage, A describes the area, $\bar{B}$ describes the magnetic field, ϕ describes the magnetic flux and I_1 is the current from the source conductor.

$$V_N = -\frac{d}{dt}\int_A \bar{B} \cdot d\bar{A} = -\frac{d\phi}{dt} = -M\frac{dI_1}{dt} \tag{8}$$

In the case of the ECG, voltage will be induced into the signals as the magnetic field passes trough the area enclosed by the lead wires when measuring on a patient. The induced voltage will be affected by the size of the enclosed area, by the wires, and its orientation relative to the magnetic field from the tramway. ECG is also affected by the magnitude of the magnetic field and in this case the distance away from the tramway, due to decay of the field with distance. The magnetic field generated by the tramway depend on position of the tram, changes in current and break in current between the tram and overhead caternary. Break in current occurs as pantograph and wire loses contact. The contact loss will create a glow discharge between the wires. When the electric field between the wire and pantograph becomes to low to drive the discharge a current break occurs.

Magnetic fields occurs when currents are traveling in a conductor, this field is described by the Bio-Savart Law. For this equation the μ_0 is the permeability of free space and r is the distance between the conductor and the place where the field is calculated.

$$\bar{B} = \frac{\mu_0}{4\pi} I_1 \oint \frac{d\bar{l} \times \hat{r}}{r^2} \tag{9}$$

The magnetic field can also be calculated from the vector potential, where this equation might be easier for the desired application. The symbols in these equations are all except $\bar{A}$ as described for the equations above, where $\bar{A}$ is the magnetic vector potential.

$$\bar{A} = \frac{\mu_0}{4\pi} I_1 \oint \frac{d\bar{l}}{r^2} \tag{10}$$

$$\bar{B} = \bigtriangledown \times \bar{A} \tag{11}$$

A magnetic field passing through a victim loop, creates a magnetic flux through it (Eq. 12). The varying flux induces a voltage in the victim circuit (Eq. 8) and hence created interference. The variables for the Eq. 12 are ϕ_2 which describes the magnetic flux through the victim loop, $\bar{B}_1$ is the magnetic field from the source conductor and $\bar{a}_2$ is the area for the victim loop.

$$\phi_2 = \int \bar{B}_1 \cdot d\bar{a}_2 \tag{12}$$

3.10.1 Magnetic fields for different geometries

Different geometries of the wires that conducts the current creates different magnetic fields. For a single wire the magnetic field produced are given in the Eq. 13. For this equation μ is the permeability of free space, I is the current from the wire, and r is the distance between the wire and the position where the field is calculated.

$$B = \frac{\mu I}{2\pi r} \tag{13}$$

For the situation with two wires where one conducts a forward current and one a return current. When the wires lays in the x-plane, the equations for y- and z-direction are given by Eq. 14.[17] For the equations for two wires and a rectangular loop, μ_0 is the permeability of free space, I is the current from the source conductor. Variables a and b be can be seen in Fig. 8, and describes the lengths in x- and y-direction of the wires, respectively. The distances r_1 to r_4 are distances between the wires and the position of calculation, seen in Fig. 8.

$$B_y = \frac{\mu_0 I}{2\pi}[\frac{z}{(y-b)^2+z^2} - \frac{z}{(y+b)^2+z^2}] \tag{14a}$$

$$B_z = \frac{\mu_0 I}{2\pi}[\frac{y+b}{(y-b)^2+z^2} - \frac{y-b}{(y+b)^2+z^2}] \tag{14b}$$

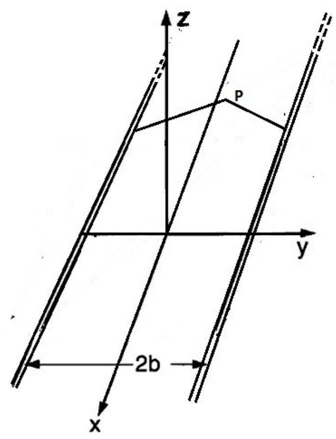


Figure 7: The layout of two wires.

The magnetic field of a rectangular loop were considering the current traveling around the loop and at an arbitrary point from it are described below.[17] Fig. 8 represent a square loop and how the variables are described.

$$B_x = \frac{\mu_0 I}{4\pi} \sum_{\alpha=1}^{4} \frac{(-1)^{\alpha+1} z}{r_\alpha (r_\alpha + d_\alpha)} \tag{15a}$$

$$B_y = \frac{\mu_0 I}{4\pi} \sum_{\alpha=1}^{4} \frac{(-1)^{\alpha+1} z}{r_\alpha (r_\alpha + (-1)^{\alpha+1} C_\alpha)} \tag{15b}$$

$$B_z = \frac{\mu_0 I}{4\pi} \sum_{\alpha=1}^{4} \left(\frac{(-1)^{\alpha} \cdot d_\alpha}{r_\alpha (r_\alpha + (-1)^{\alpha+1} C_\alpha)} - \frac{C_\alpha}{r_\alpha (r_\alpha + d_\alpha)} \right) \tag{15c}$$

and the constants are

$$\begin{aligned} C_1 &= -C_4 = a + x & r_1 &= \sqrt{(a+x)^2 + (y+b)^2 + z^2} \\ C_2 &= -C_3 = a - x & r_2 &= \sqrt{(a-x)^2 + (y+b)^2 + z^2} \\ d_1 &= d_2 = y + b & r_3 &= \sqrt{(a-x)^2 + (y-b)^2 + z^2} \\ d_3 &= d_4 = y - b & r_4 &= \sqrt{(a+x)^2 + (y-b)^2 + z^2} \end{aligned}$$

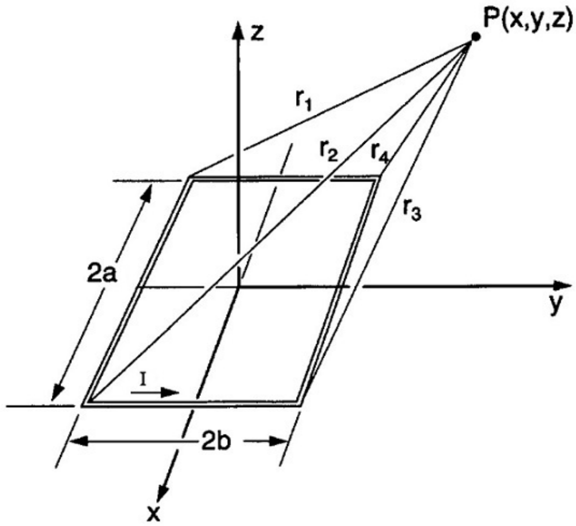


Figure 8: A square loop and its parameters.
[18]

This field is calculated for four straight wires and for an arbitrary point in space. The arbitrary point is considered for the victim loop. The largest induction occurs as the magnetic flux passes straight through the loop, which happens in z-direction, when the loop is flat in the x-y plane.[2] [16] [18] [17] [19]

3.11 Reduction and shielding of magnetic fields

To reduce inductance into a loop the simplest solution is to reduce the size of the loop, why it is crucial to know the currents path through a circuit. To change the orientation of the victim loop so that less field will travel through it and induce a voltage also reduces the induction. Shielding is used to guard the equipment from fields coupling into the device, and hence reduce the field strength. It can also be used to control how the electric and magnetic fields propagates from one region to another and between medias. In the case of a radiated wave in the near field the magnetic and the electric fields have to be considered separately when shielding. Magnetic shielding is achieved if a grounded and nonmagnetic shield is placed around the victim conductor, though grounding of the shield must be accomplished at both ends of the shield. Shielding occurs as the induced voltage in the shield counteracts the voltage induced in the victim source, Fig. 9.

If the field in another cases travels through a shielding/screening material the reduction in field is due to both absorption, reflection losses and a correction factor. The depth at which the wave is attenuated a factor of 1/e is called skin depth and at this depth the absorption loss will be about 9dB. Absorption will be almost constant no matter if a magnetic or electric field is considered. In the opposite way the reflection loss will be due to the difference in characteristic impedance between the medias that the wave propagates between, which differs between an electric and magnetic field. For a magnetic field multiple reflections will occur and reduce the shields effect. [16] [20]

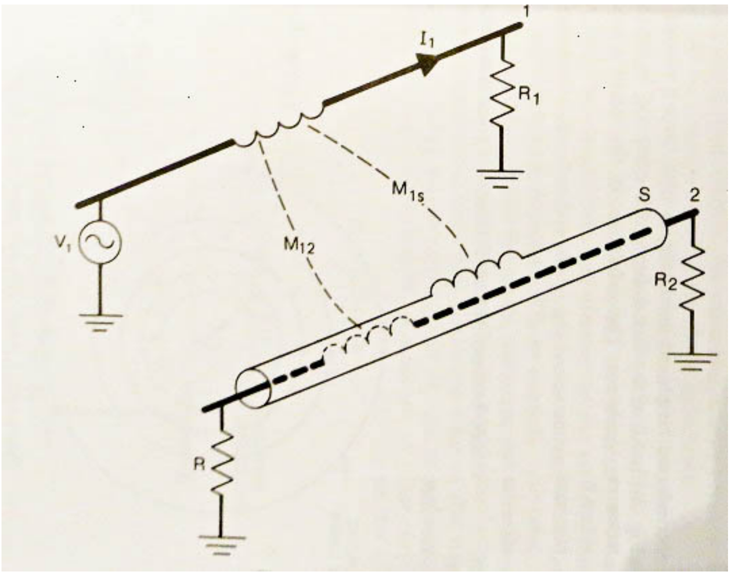


Figure 9: The source conductor with a current I_1 induces a voltage into the victim conductor. The shield around the victim conductor will create a shield current due to the indcued voltage in the shield that occurs beacuse of the magnetic coupling between the shield and the source conductor.[20]

3.12 Immunity

Immunity is the product's ability to tolerate the electronic energy's influence from other products and electromagnetic phenomena. It is of importance to investigate whether the electronic equipment works as it should when it is affected by an outward field. For the ECG signals, their immunity level should be above the highest signal that will be measured. [2] [21]

3.13 Glow discharge

As two conductors looses contact the air between them becomes ionized and such creates a spark. During the sparking the current between the conductors is still flowing. This spark when occurring between the overhead caternary and the pantograph creates a spark gap transmitter. The spark will in the section of the caternary create a standing wave. This caternary in a tramway acts as an antenna and creates a magnetic field in the order of kHz or MHz depending on the section length.[2][20]

3.14 Amplifiers

3.14.1 Differential amplifier

Differential amplifiers accepts two input signals and amplifies the difference between the two inputs. It takes the difference by subtracting one signal from the other. In these amplifiers, signals common for both inputs will be canceled out, which will reduce the noise in the amplifier.[22]

3.14.2 Operational amplifiers

An Operational amplifier, (op-amp), is a DC-coupled differential amplifier that has a high gain. An op-amp receives two input signals and returns one, which is the differential between the input signals, where the amplification will be due to the connected resistors. The signal can be amplified in the op-amp up to a thousand times the original signal, depending on how the amplifier is programmed. The amplifier is coupled to two dc supplies to be able to operate, with one negative and one positive with respect to the ground. Ground is the common point between the two power supplies. As the output voltage gets close to the power supply level it will make the transistors in the amp saturate. To never reach the saturation level, a margin of 2V to the supply limit is recommended. The op amp has a small offset at the output, which exist even when there is zero difference between the inputs. There are also some AC noise generated in an op amp, why a lower limit on signals to amplify. [23] [24]

3.14.3 Instrumentation amplifiers

One type of the differential amplifier is the instrumentation amplifier that is widely used when small signals are supposed to be amplified. In these amplifiers the resistors in the circuit determines the gain. The amplifier amplifies the voltage difference between two input signals while rejecting common signals. This amplifier can be constructed from op amps and the output will be determined from Eq. 16.[25]

$$\frac{V_{out}}{V_2 - V_1} = (1 + \frac{2R_1}{R_{gain}})\frac{R_3}{R_2} \tag{16}$$

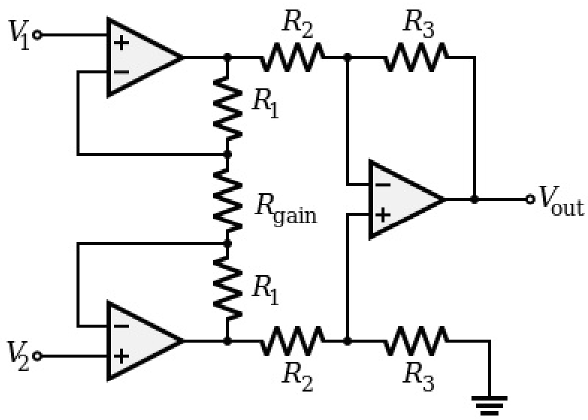


Figure 10: The electical circuit of an Instrumentation amplifier. [26]

3.15 Rectifier

A rectifier is an electronic component that converts voltage with both negative and positive polarities to only be composed of one of these two, so as to convert ac current to dc current. Rectifiers are often composed of diodes and lets only through peaks of the desired polarity of the signal. In the ideal case a diode that lets through positive signals, lets the signal through linearly from 0V and onward. Below 0V the ideal diode blocks the signal completely as it is reversed biased below 0V, whereas a diode that lets through negative voltages blocks the positive signals. However real diodes lets the current through only above normally 0.7V, though this break is not totally sharp. Instead it lets through voltage between 0V and 0.7V, where the amount of current increases as it gets closer to 0.7V. The same goes for diodes for negative voltage, though in reverse. If the reverse voltage is to large, the voltage that the diode should block will start to seep through.

A rectifier will produce a signal in the form of a pulsating DC signal, where the pulsation is called ripple. To reduce ripple a capacitor can be coupled into the circuit, to reduce the voltage drop between cycles. The capacitor need to be big enough, so as not to uncharge during low voltage, though a certain amount of drop will still happen and ripple will occur.The ripple can also be smoothed by a filter circuit.

In the case with only one diode, only half wave rectification are achieved, where the signal is let through when it possesses one of the polarities and are rejected otherwise. This leads to a signal where the wave becomes zero when it possesses the polarity of the rejected voltage. If it is desired to convert both polarities, so as to convert one polarity to its opposite sign a full wave rectification is needed. In which case two diodes will be used, where one is conducting and one is open when the signal is of one polarity and then in the case where the polarity is turned the conducting and open diodes are switched. In which direction through the diodes the current flows depends on which part of the conductor is positive in comparison to the other. The diodes are coupled so as that they supply the same resistance. In a bridge rectifier, four diodes are connected in such a way that when the voltage is positive two diodes will be forward biased and the other two will be reversed biased. In the case where the voltage is negative the forward and reversed biased diodes are changed. The output current will be of the desired polarity, no matter the polarity of the input current. Stopping of voltage drop between cycles in the signal after rectification a capacitor can be coupled in the circuit, so as to stop the voltage from decreasing. Though a certain amount of drop will happen and ripple will still occur. To reduce the ripple a big enough capacitance is needed, so as not to uncharged during low voltage.

The rectification in tramways current supply are accomplished by a 6-pulse or 12-pulse rectification, where the 6-pulse rectification is accomplished by three full wave rectifiers and 12-phase by two three phase rectifications in parallel. [2] [12] [23] [27] [28]

3.16 Patient Monitor - Philips IntelliVue

A patient monitor is designed to monitor and display physiological parameters in adults, children and neonatal patients. ECG monitoring is used for diagnostics and registration of the morphology of the heart. The monitor has for ECG signals a band pass filter to remove unwanted signals.(Table 1) The signals are registered through a measurement module that are connected to the monitor. This module registers physiological parameters, where on of these is the ECG leads. To the module the patient cable is connected, which is a cable gathering together the signals from the ECG lead wires, these wires are connected to electrodes on the body surface. The wires have different color to indicate where they should be connected onto the body, a green wire connects to the left leg, a black wire connects to the right leg, a red wire connects to the right arm, a yellow wire connects to the left arm and the white wire should be conduced to the chest. This is the configuration used in Europe. The pin configuration for the connection into the monitor can be seen in Fig. 11. [10] [29]

Bandwidth	Diagnostic mode	Adult/children/neonatal: 0.05 to 150Hz
	Extended Monitoring Mode	children/neonatal: 0.5 to 150Hz
	Monitoring mode	Adult: 0.5 to 40Hz
	Monitoring mode	Children/neonatal: 0.5 to 40Hz
	Filter mode	Adult/children/neonatal: 0.5 to 20Hz

Table 1: The filter modes.

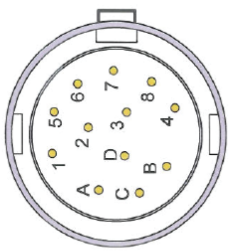


Figure 11: Pin figuration of the ECG cable [29]

Electrode Labels	Pin
RA	1
LA	7
LL	6
RL	2
Ground	C

Table 2: The Pins representing different leads. [29][10]

3.17 ECG simulator

Bio tek model ECG-I can simulate ECG signals and square signals. These signals can have frequencies 30,60,120,180Hz and voltages of 0.5,1,1.5 and 2mV.

4 Method

Theoretical modeling and experimental measurements were made to simulate whether any interference on the ECG signals would occur from the magnetic fields created by the tramway. Modeling and calculations had been made by a consultant at the request of Skånes University hospital. In this thesis, the same simulations and those missing for the experiment are recreated with a simpler model. All calculations were made in Matlab. Which experimental measurements should be made were deduced from the cases presented by Dick van Bekkum and the mathematical modeling. An electromagnet was manufactured to simulate the different magnetic fields; the disturbances occurred from a accelerating/decelerating, contact loss and current ripple.[2]

4.1 Modeled interference

Ripple for a six- and twelve-phase rectified 750V voltage were simulated and transformed into the frequency plane. The rectified signal was a 50Hz sinusoidal signal, so as to represent the AC voltage in Swedish power lines. With a six and a twelve phase rectification a ripple of 300Hz and 600Hz with harmonics were created. Simulations were constructed for a Hanning-windowed FFT, to analyse how large the interference was and whether the desired signals and their harmonics were contained in the signal. Acceleration and deceleration of the trams were simulated as a decaying current from 1200A to zero. The decay were simulated for both 1s and 3.5s decay. Simulations of the exponential decay due to loss of contact between tram and the track, were simulated for a current decaying from 1200A to 0A. Simulations were analyzed in the frequency plane. All simulations were made for distances 25meter and 10meter, where the tram tracks were simulated as two parallel wires. The magnetic field from the electromagnet and the tram at different currents and distances were implemented in Matlab, for details see sections below. [2]

4.2 Simulations and Lab measurements

Some measurements were made by the use of an instrumentation amplifier. Which had an calculated amplification factor of 7458 (Eq. 16) and a low pass filer on the input, with a -3dB cut off at 2000Hz. This amplifier used the resistances $R_1 = 300k\Omega$, $R_{gain} = 300\Omega$, $R_2 = 22k\Omega$ and $R_4 = 82k\Omega$.

An electromagnet was manufactured and driven by a voltage source to simulate the magnetic field generated by the tramway. The magnet was constructed from a copper wire, which had been wound to a coil. The coil was made as a quadrat with 25.5cm long sides with 66 turns. The magnet was placed so that the magnetic field in the z-directions passed through the area enclosed by the wires. The magnets field in the z-direction was calculated by the equation below.

$$B_z = \frac{\mu_0 I}{4\pi} \sum_{\alpha=1}^{10} \left(\frac{(-1)^\alpha \cdot d_\alpha}{r_\alpha(r_\alpha + (-1)^{\alpha+1} C_\alpha)} - \frac{C_\alpha}{r_\alpha(r_\alpha + d_\alpha)} \right) \tag{17}$$

To induce a disturbance caused by the magnetic field into the ECG signals, the wires for different leads were taped to the wall, so as to have a flat area which the magnetic field passed through.(Fig. 12) Different leads had different sized areas, as the wires for the different leads had different lengths. The area was made as large as possible, to create a worst case scenario, though in a real life situation this area would advantageously be kept small. In the case of no area enclosed by wires there would theoretically be no inductance, and thereby no interference. The areas enclosed by the wires are shown in Table 3.

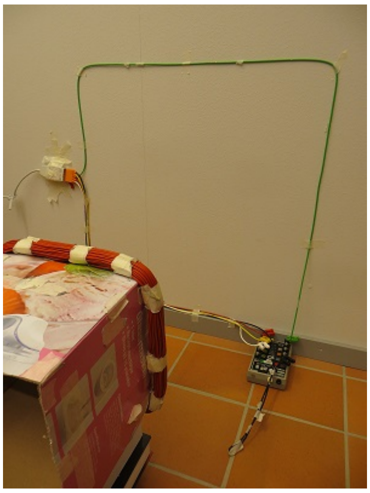


Figure 12: The setup for the experimental measurements. The ECG wires are taped to the wall and connected to an ECG simulator, shown to the right in the picture, and then connected to either a monitor or an amplifier and oscilloscope. In front of the wires the electromagnet is placed, can be seen in the low left corner.

Measurement	**Color**	**Area Monitor**	**Area Oscilloscope**
Acceleration/Deceleration	Green	$0.58 \cdot 0.58m^2$	$0.54 \cdot 0.62m^2$
Acceleration/Deceleration	Black	$0.58 \cdot 0.58m^2$	$0.54 \cdot 0.62m^2$
Acceleration/Deceleration	Red	$0.44 \cdot 0.455m^2$	$0.42 \cdot 0.45m^2$
Acceleration/Deceleration	Yellow	$0.44 \cdot 0.455m^2$	$0.42 \cdot 0.45m^2$
Acceleration/Deceleration	White	$0.44 \cdot 0.455m^2$	$0.42 \cdot 0.45m^2$
Acceleration/Deceleration	Noarea	No area	No area
Current break	Green	$0.44 \cdot 0.455m^2$	$0.32 \cdot 0.39m^2$
Current break	Black	$0.44 \cdot 0.455m^2$	$0.32 \cdot 0.39m^2$
Current break	Red	$0.44 \cdot 0.455m^2$	$0.39 \cdot 0.49m^2$
Current break	Yellow	$0.44 \cdot 0.455m^2$	$0.39 \cdot 0.49m^2$
Current break	White	$0.44 \cdot 0.455m^2$	$0.39 \cdot 0.49m^2$
Current break	Noarea	No area	No area
Ripple	Green	$0.60 \cdot 0.60m^2$	$0.57 \cdot 0.63m^2$
Ripple	Black	$0.54 \cdot 0.62m^2$	$0.57 \cdot 0.63m^2$
Ripple	Red	$0.36 \cdot 0.47m^2$	$0.41 \cdot 0.45m^2$
Ripple	Yellow	$0.34 \cdot 0.49m^2$	$0.41 \cdot 0.45m^2$
Ripple	White	$0.35 \cdot 0.51m^2$	$0.41 \cdot 0.45m^2$
Ripple	Noarea	No area	No area

Table 3: The area enclosed by the wires, for the measurements of acceleration/deceleration, current break and ripple for the monitor and oscilloscope setup.

The measurements were all made for the scenarios presented earlier, ripple, acceleration/deceleration and current break. Where the simulation of ripple was made for the current of 1200A and 3200A, acceleration/deceleration were made for the current of a tram, 1200A and so was the current break. These interferences were simulated for a distance of 10meter and 25meter. A simulation for the case at 10 meters, were to see how equipment in the IT/MT department of Skånes University hospital, Lund, and potential new buildings, would be affected by the tramway. The distance 25meter was used to simulate the magnetic field for the rest of the hospital in Lund as the remaining buildings of the hospital are at this distance or further away. Since the magnetic field from the trams decays with the square of the distance, if there are no noticeable disturbances at this distance none would exist beyond this distance either.

For different cases of disturbances the magnetic fields were calculated for each one of the distances and currents of the tram system, the same magnetic field was then calculated for the magnet. This showed at what distance the magnet should be placed to produce the desired magnetic field. The field from the magnet through the area enclosed by the wires, was calculated so that the uniform field was equal to the field generated by the trams at the distances that were simulated. These distances were 10meters and 25meters, where the field for the distance 25meters used the fields described in the report by Dick van Bekkum and the fields for a distance of 10meters was calculated with the tram simulated as two parallel wires.

The ripple was simulated both with a 600Hz and 300Hz rectified sinusoidal, where the magnetic field was proportional to the varying current of the ripple. The rectification was made so that only the positive peaks were let through, though when the signal were theoretically zero a voltage of -0.8V could be measured. The rectification was used so as to introduce harmonics in the signal, which will occur for the rectification of current to a tram system. Here a TG1010 DDS function generator was used to produce the sinusoidal signals and an in house design amplifier were connected to amplify the signals. Connected to the amplifier were the rectifier and electromagnet, which had a resistance of 2.4Ω. The signal amplitude in volt was measured with an oscilloscope. These values were used to calculate at what distance the magnetic field would represent the field from the ripple on the tram track, where the voltage and current are related as follows, $U = R \cdot I + L\frac{di}{dt}$. The voltage of the ripple from the tram track will only be a fraction of the total voltage on the track, 13.5% and 3.4% for 300Hz and 600Hz respectively. The ripple creates a varying magnetic field that is a fraction of the total magnetic field for a theoretically varying voltage of 750V. These simulations were made for the tram track correspondingly to a current of 3200A and the trams current of 1200A at a distanced 10meters and 25meters, respectively.

The exponentially decaying signal from the current break was created using a square signal from the function generator. The signal had a frequency of 1Hz to introduce the interference in every heartbeat. This signal became an exponentially decaying signal as it became distorted by the magnet and due to the function generator not being entirely able to produce a square wave at such a low frequency. The signal was simulated so that it represented a decay from 1200A to zero. Experiments were simulated for both the 10meter and 25meter cases.

Acceleration and deceleration between 1200A and 0A were simulated with a current generator, Powerbox3000, where a specific current could delivered to the coil. The signal was connected to the magnet directly from the current generator. From this a current of 2.5A was used. This setup was also connected to an oscilloscope so as to see the decay rate. The decay was achieved manually by decreasing the current from 2.5A to zero in 1s and 3.5s to simulate different situations of decay.[2]

All measurements were made with the two different setups one connecting the wires to the ECG monitor, and one connecting the wires to an amplifier and oscilloscope setup. The ECG monitor, IntelliVue MP70, was connected to the ECG simulator, Bio Tek ECG Model I, through the ECG cables. However, this monitor has a band pass filter between 0.05Hz to 150Hz, which is the broadest of the filters available in the monitor, some signals above 150Hz are possible to detect. Because of this filter, measurements with an amplifier connected to an oscilloscope were also made. In this case the pins of the ECG cable were connected to the amplifier,(Fig. 2). For each signal, ground was connected to the ECG pin for grounding. The bipolar limb leads were measured by connecting each pin of the two signals that should be compared to one of the input connectors. For the unipolar limb leads two of the signals were connected through one resistance of 1kΩ each, and then connected to the amplifier. The third signal, that the combined signals should be compared to, was connected directly to the other input of the amplifier. To power the amplifier or more correctly the op amps with a voltage of ±15V the amplifier was connected to a current generator, University Power 3535.

The signals were then analyzed in the frequency plane, where they were compared to the frequencies of a normal signal, with no interference.

4.3 Real life measurements

Measurements were made in Göteborg, next the tram track at 10meters and 25meters. Measurements were made by the monitor and only for areas of the green and red lead wires, areas for these are presented in the results section. When measuring, the monitor was placed inside the car and the ECG simulator and wires were placed outside. The wires were taped to a box, to provide an area which the field could pass through. This box was placed either standing up directed toward the tramway or parallel to the ground(Fig. 13 and Fig. 14). The equipment was powered by a trailer battery with a DC to AC converter, which also were outside of the car. As measurement were made the times for the passing trams, related to the time for the start of the measurement, their direction, tram line and tram number were registered. In Göteborg the trams run on 1200-1500A and the maximum current on the wire is around 3000A. The trams are powered by a 6-phase rectifier, whereas a ripple of 300Hz exists. For some measurements the computer was connected to a second trailer battery and converter, some distance away from the ECG wires. Signal without any interfering trams had some disturbances introduced from the converter connected to the monitor, (Fig.15). [12] [15]

Figure 13: The setup for the measurements in Göteborg. The wires were taped to a box, which lay down on the ground or was placed standing. Inside the car the monitor is seen. In the righ hand picture a trailer battery and a converter is seen, which were used to power the monitor.

Figure 14: The setup in Göteborg next to the tramway. The box where the wires were taped can be seen standing up and directed towards the tramway. Inside the car is the monitor.

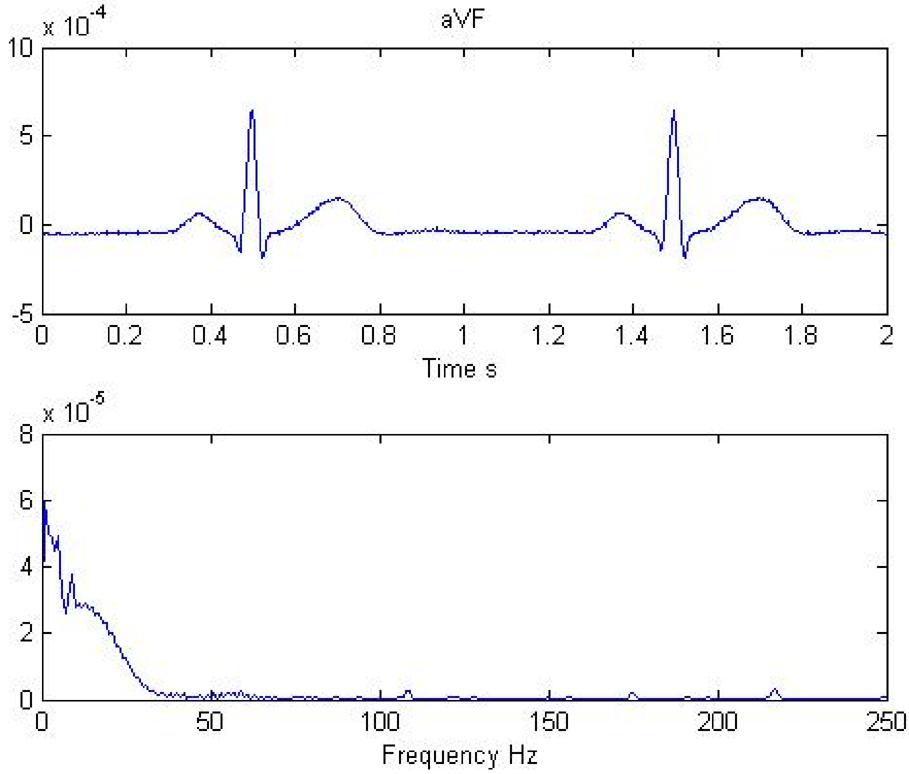


Figure 15: The ECG signal with disturbances from the DC to AC converter, with visible peaks at places 110, 175 and 220Hz.

5 Results

5.1 Calculated effects

The changes in the magnetic field and voltage represents the cases of ripple, acceleration/deceleration and current break. The signals are presented in the frequency plane as to see whether they interfere with the ECG signals which usually uses frequencies up to 150Hz, even though high frequency ECG up to 250Hz exist and may develop to clinical practice in the future. The magnitude of the magnetic fields for currents of 1200A and 3200A from a tram track at a distance of 10meters are $12.3\mu T$ and $33.1\mu T$ respectively. For acceleration/deceleration an induced voltage of $14.3\mu V$ would be achieved at 10 meter and for current break a voltage of $5.3mV$ would be induced in a $1m^2$ loop, where the induction can be calculated with Eq. 8. The change in magnetic field can be calculated from the frequency plane where 19bins over a span of 3000Hz has been used, which gives a total magnetic field as described here $B = \sum B_n \cdot cos(2\pi \cdot n \cdot 152.6 \cdot t)$, where n=1..19, t is the time, B is the total magnetic field, B_n the field in a bin and 152.6 the bandwidth of teach bin.

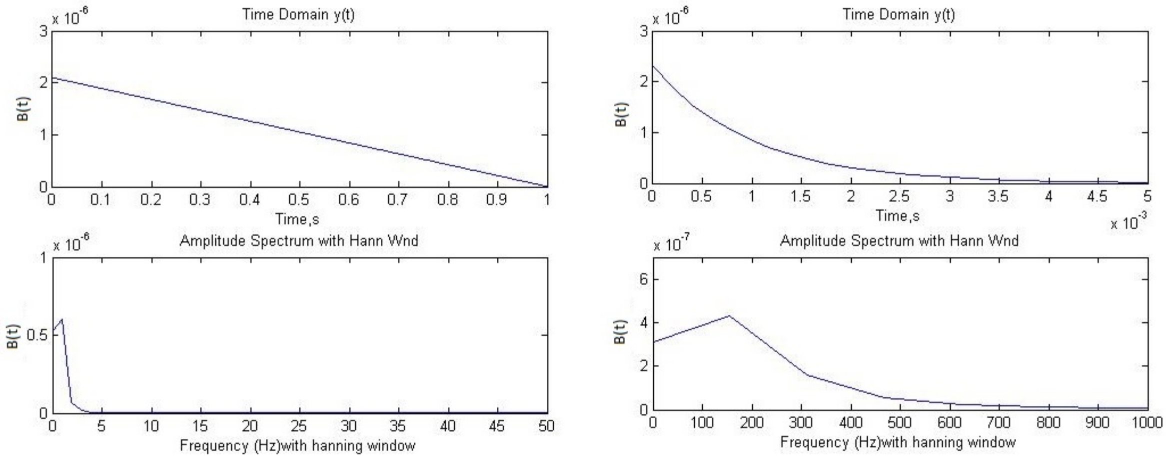


Figure 16: Simulations of Acceleration/Deceleration (left) and current break (right) in time domain and frequency domain

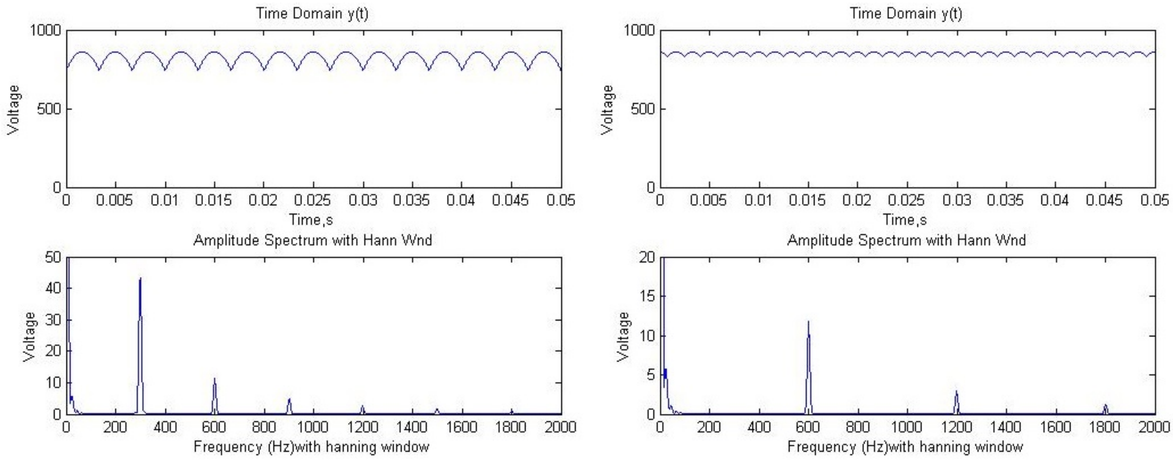


Figure 17: The two cases of ripple and the signals in the frequency domain. 300Hz ripple to the left and to the right 600Hz ripple.

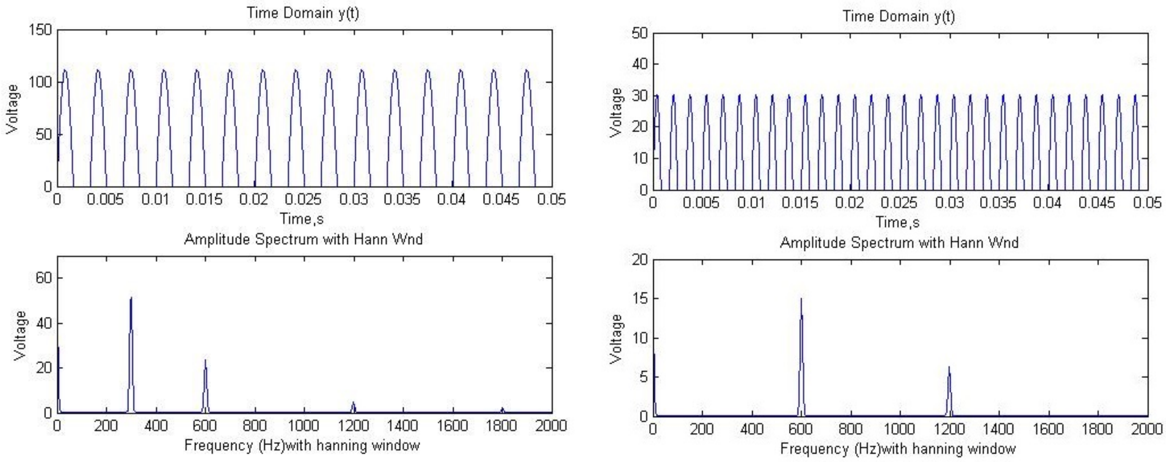


Figure 18: The ripple used in the experiments and the signal in the frequency plane. 300Hz ripple to the left, to the right 600Hz ripple.

5.2 Experimental Measurements

5.2.1 Accelerating/Decelerating tram

These measurements simulated the tram braking in 1 second, an absolute worst case scenario, and 3.5 seconds. An emergency brake will make the tram decelerate from maximum speed to zero in 3.5 second.[2] The decrease considered are from 1200A to zero, the current of a single tram. In figures below no interference for a braking tram is visible, this was also shown in calculations to compare this signal to a signal with no interference.

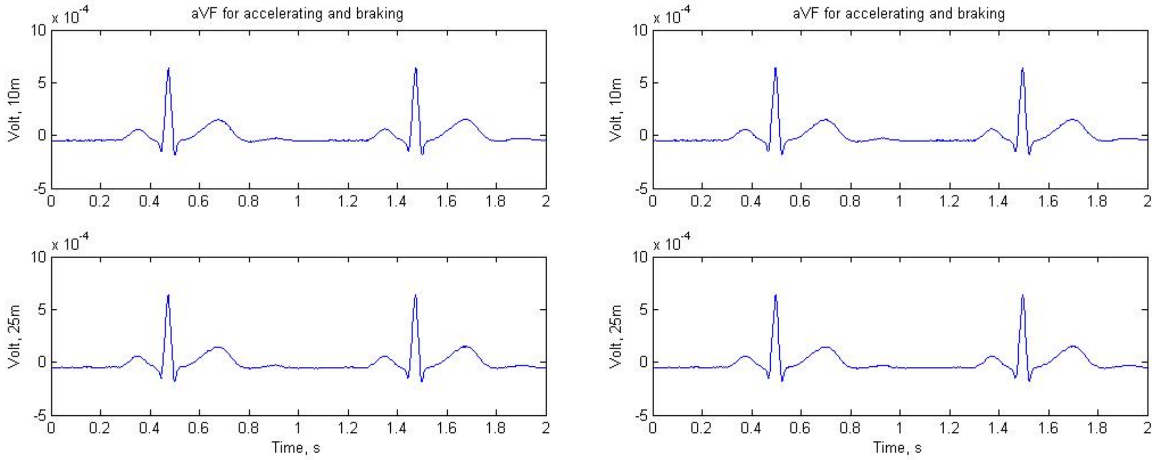


Figure 19: The signals when there is a tram accelerating/decelerating registered with the monitor. Left figure are for 1s decay and right 3.5s decay.

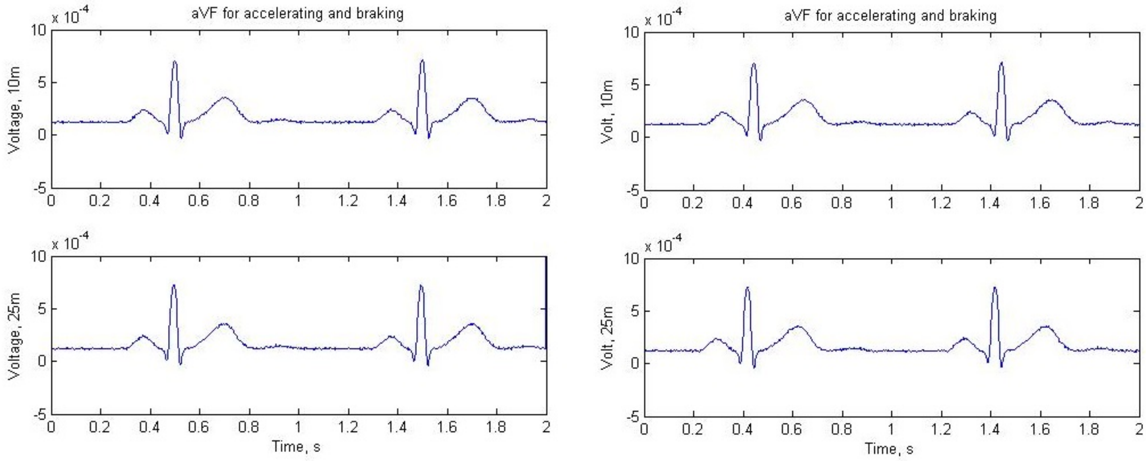


Figure 20: The signals when there is a tram accelerating/decelerating registered with oscilloscope. Left figure are for 1s decay and right 3.5s decay.

5.2.2 Exponential decay

A tram losing contact with the over head catenary will make the current decay rapidly and exponentially.[2] Experimentally no noticeable interference occur for the simulation of the field at 25m.(Fig. 21, Fig. 22) Neither is there interfering signals for the monitor at 10m. The signal, where the wires were connected to an amplifier and then an oscilloscope, shows interfering spikes at the time of the decaying current when a distance of 10m is simulated. Simulation occurs as a square wave is used, where the distance between the magnet and ECG wires and the magnitude of the field represents the one at 10 meters from the tramway.

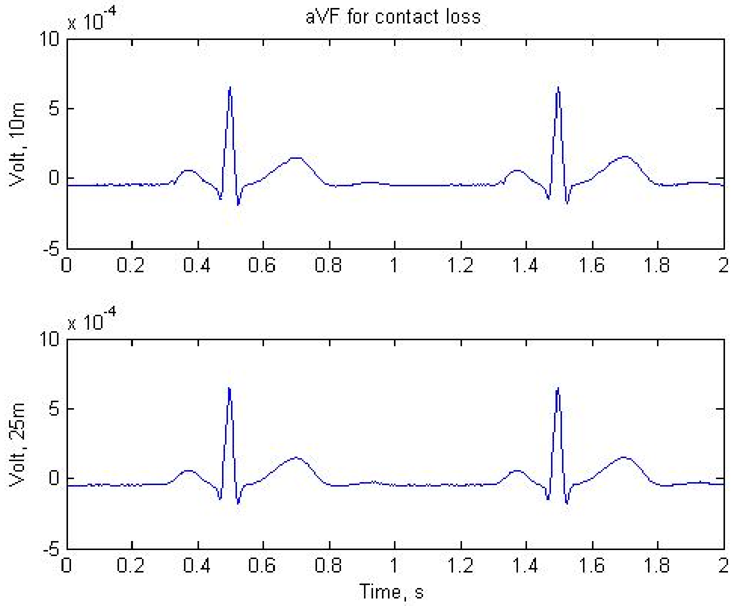


Figure 21: The signals when there is a tram losing contact with the overhead catenary wire registered with the monitor.

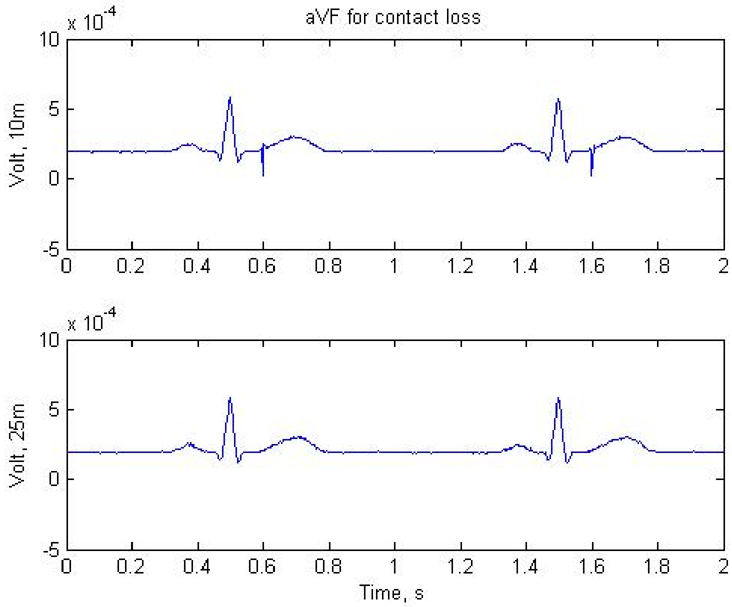


Figure 22: The signals when there is a tram losing contact with the overhead catenary wire registered with the oscilloscope.

5.3 AC Ripple on the DC current

5.3.1 Monitor

AC ripple on DC current to the tram introduces a certain amount of interference into the ECG signals. The size of the ripple current represents 13% and 3.5% for 300Hz and 600Hz respectively of the current in either a whole system or a single tram. The signals and the magnitude of the interference for the monitor (Fig. 23,Fig. 24,Fig. 25) shows that for a system where the maximum current of 3200A is considered a large interference are induced at a distance of 10m, though at 25m the interference is quite small. The induced voltage for a 6-pulse rectification, ripple of 300Hz, in the green wire for the signals II, aVR, aVL, aVF are large with a magnitude in the order of 10^{-5}V. The case where the red wire encloses an area induction in the signals I,II, aVR are in the order of 10^{-5}V, and for the signal of the yellow wire enclosing an area induction for I, aVR, aVL and aVF are in the order of 10^{-5}V, for 6-pulse rectification. All other signals for these wires are below 10^{-5}V. For the the wire configuration of black, whit and no area low interferences are induced. In the case of current for a single tram smaller interference can be seen at the distance of 10m and no interference occurs at 25m. A 12-pulse rectification, ripple of 600Hz, induced no interfering signals, as the magnitude of the signals at interfering frequency are in the order of the background noise in the signal. The magnitude of the background noise is in the order of 10^{-7}V for both cases 300Hz and 600Hz.

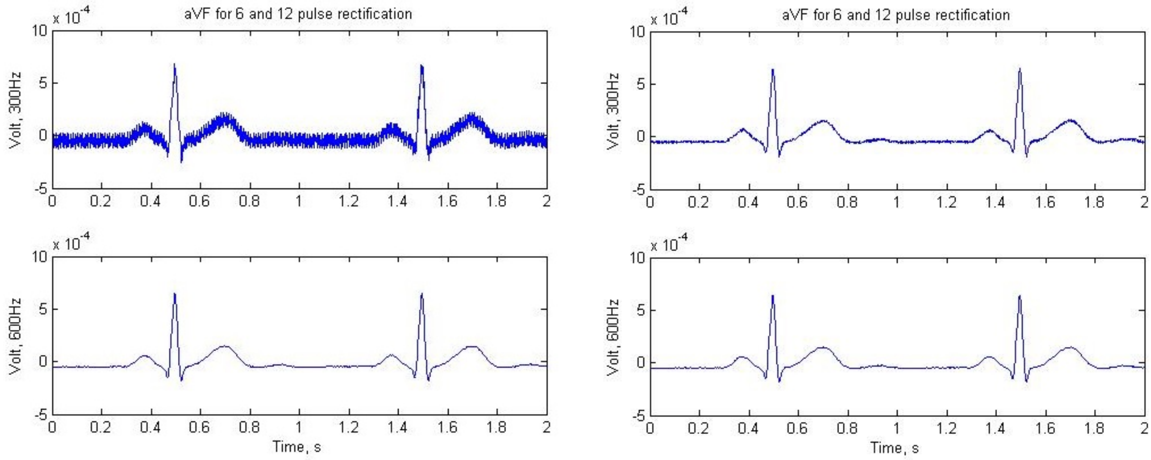


Figure 23: Induced ripple for a current going in the overhead catenary wire and returning via the track, for a system of 3200A. Measured with the monitor. The left side presents the signals with a rectification of 6-pulse (upper) and 12-pulse (lower) for a distance of 10m, while the right shows the same for a distance of 25m.

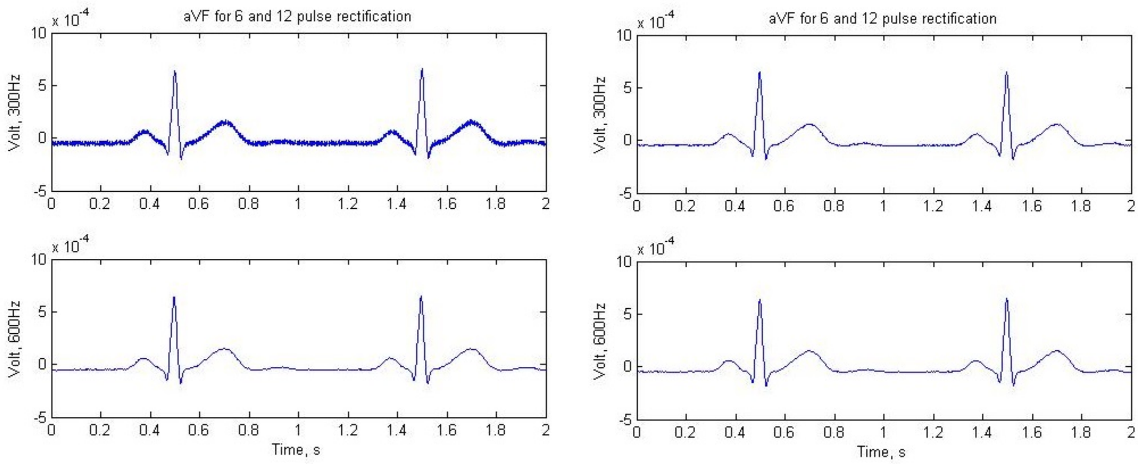


Figure 24: Induced ripple from a current going in the overhead catenary wire and returning via the track, for the current of only one tram, 1200A. Measured with the monitor.The left side presents the signals with a rectification of 6-pulse (upper) and 12-pulse (lower) for a distance of 10m, while the right shows the same for a distance of 25m.

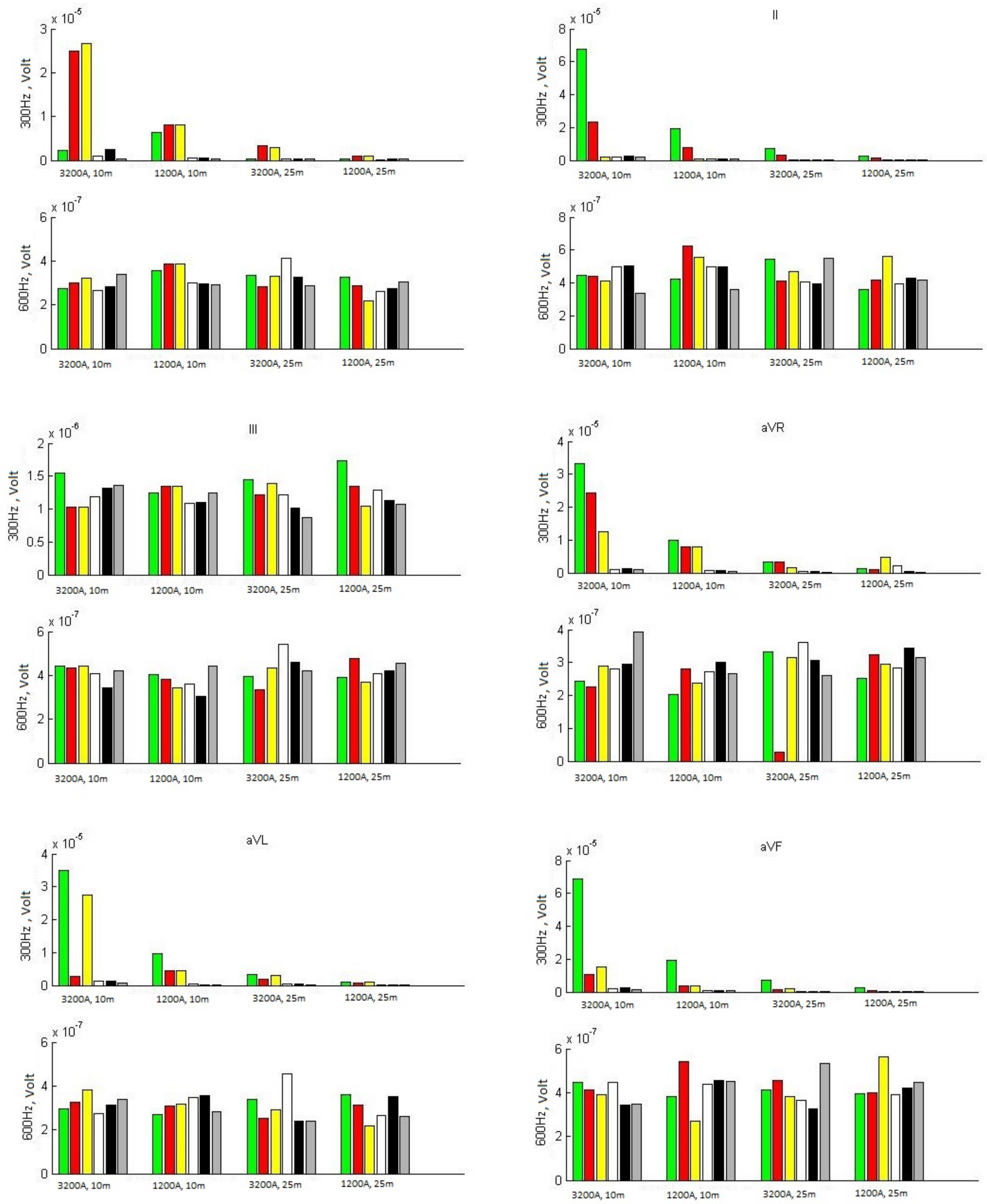


Figure 25: The magnitude of the ripple for all enclosed areas and and limb leads. The upper plot in each subplot for the specific lead shows the magnitude for a 300Hz (6-pulse rectification) interference and the lower plot in the subplots shows the disturbance for a 600Hz (12-pulse rectification) interference. In each subplot the magnitude of the cases, 3200A at 10m, 1200A at 10m, 3200A at 25m and 1200A at 25m, are shown. The colors represents the wires enclosing an area.

5.3.2 Oscilloscope

Signals measured with an amplifier and oscilloscope shows a larger interference than for the monitor, likely due to the monitor having a filter. A system where the maximum current of 3200A is considered, a large interference is induced at a distance of 10m, though at 25m the interference is much lower, though still noticeable. (Fig. 26) All limb leads has an interfering signal in the order of 10^{-5}V for the red and yellow wires for a 6-pulse rectification at a distance of 10m. The rectification will have harmonics, and among them are 600Hz, which also induces a large interference into the signal, and are for some leads still in the order of 10^{-5}V. The green wire has a large interference in the leads II, III and aVF, which is in the order of 10^{-4}V at 300Hz and for the 600Hz harmonic a magnitude of 10^{-5}V at a distance of 10m. The leads of aVR and aVF has a magnitude of interference of 10^{-5}V, both for the 300Hz and 600Hz harmonics, while the lead I is much lower. The wires white, black and no area have a low inductance in all leads. Considering the current from a single tram a much smaller interference can be seen at the distance of 10m, and is almost not noticeable at the distance 25m.

Interference from a 12-pulse rectification can be seen for the current of the whole system at a distance of 10m, the other scenarios create a small interference. The interference, though smaller than for a 6-pulse rectification are still in the order or 10^{-5}V for the current of whole system at 10m, especially for the green, red and yellow wires.(Fig. 30). Wire configurations of black, white and noarea shows low interference for all current scenarios.

The figures 26, 27 and 28 shows clearly a large disturbance in the ECG signal in the case with the whole system for 6-pulse rectification and at a distance of 10m. Even a 12-phase rectification will induce disturbance in the signal at 10m. A distance of 25m will reduce the disturbing signal significantly.

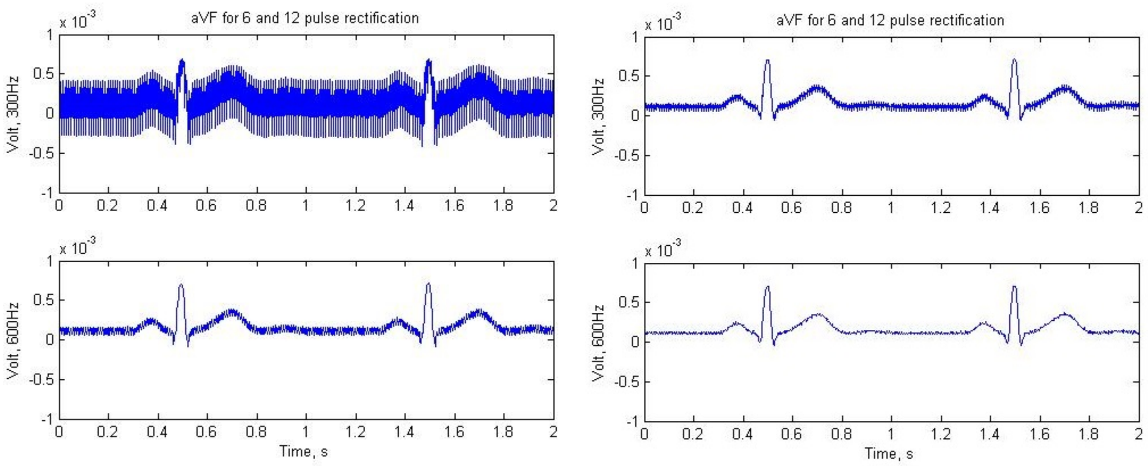


Figure 26: Induced ripple from a current going in the overhead catenary wire and returning via the track, for a system drawing 3200A. Measured with the oscilloscope. The left side presents the signals with a rectification of 6-pulse (upper) and 12-pulse (lower) for a distance of 10m, while the right shows the same for a distance of 25m.

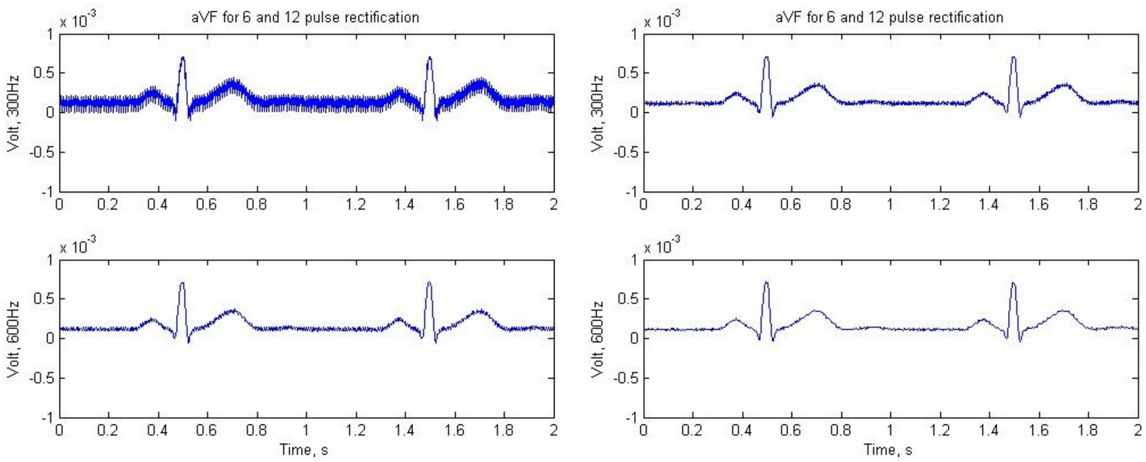


Figure 27: Induced ripple from current going in the overhead catenary wire and returning via the track, for the current of only one tram, 1200A. Measured with the oscilloscope.The right side presents the signals with a rectification of 6-pulse (upper) and 12-pulse (lower) for a distance of 10m, while the right shows the same for a distance of 25m.

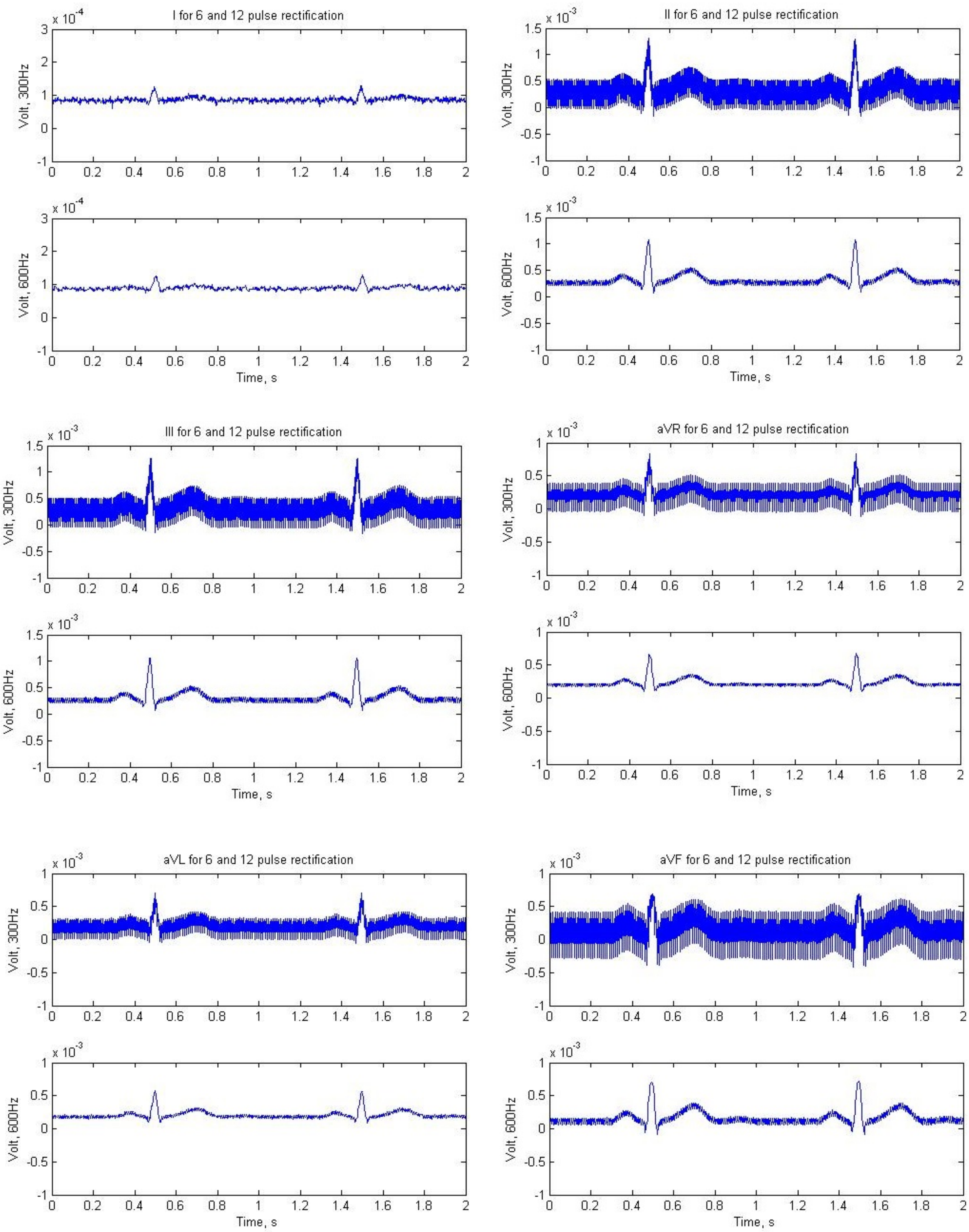


Figure 28: Induced ripple from current going in the overhead catenary wire and returning via the track, for a system of 3200, measured with the oscilloscope. The plots show the cases of 6-pulse rectification and 12-pulse rectification for all the limb leads. Each plot for the leads has two subplots, where the upper one of the subplots show the 6-pulse rectification (the label in y-led for the plot is 300Hz) and the lower subplot shows a 12-pulse rectification (the label in y-led is 600Hz). Which lead is shown is described in the headings of the plots.

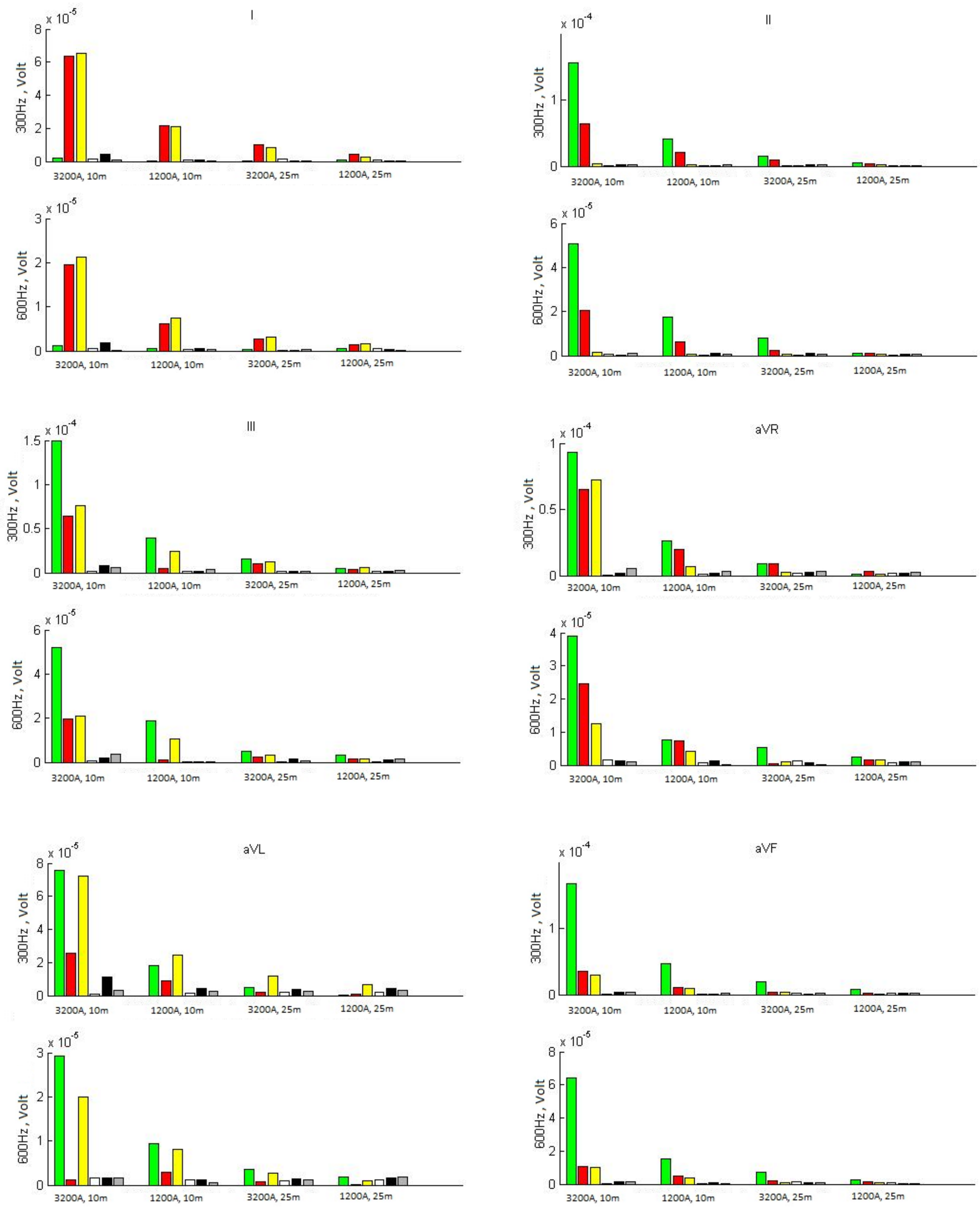


Figure 29: The magnitude of the ripple for all enclosed areas and and limb leads. The upper plot in each subplot for the specific lead shows the magnitude for a 300Hz (6-pulse rectification) interference and the lower plot in the subplots shows the disturbance for a 600Hz harmonic interference. In each subplot the magnitude of the cases, 3200A at 10m, 1200A at 10m, 3200A at 25m and 1200A at 25m, are shown. The colors represents the wires enclosing an area.

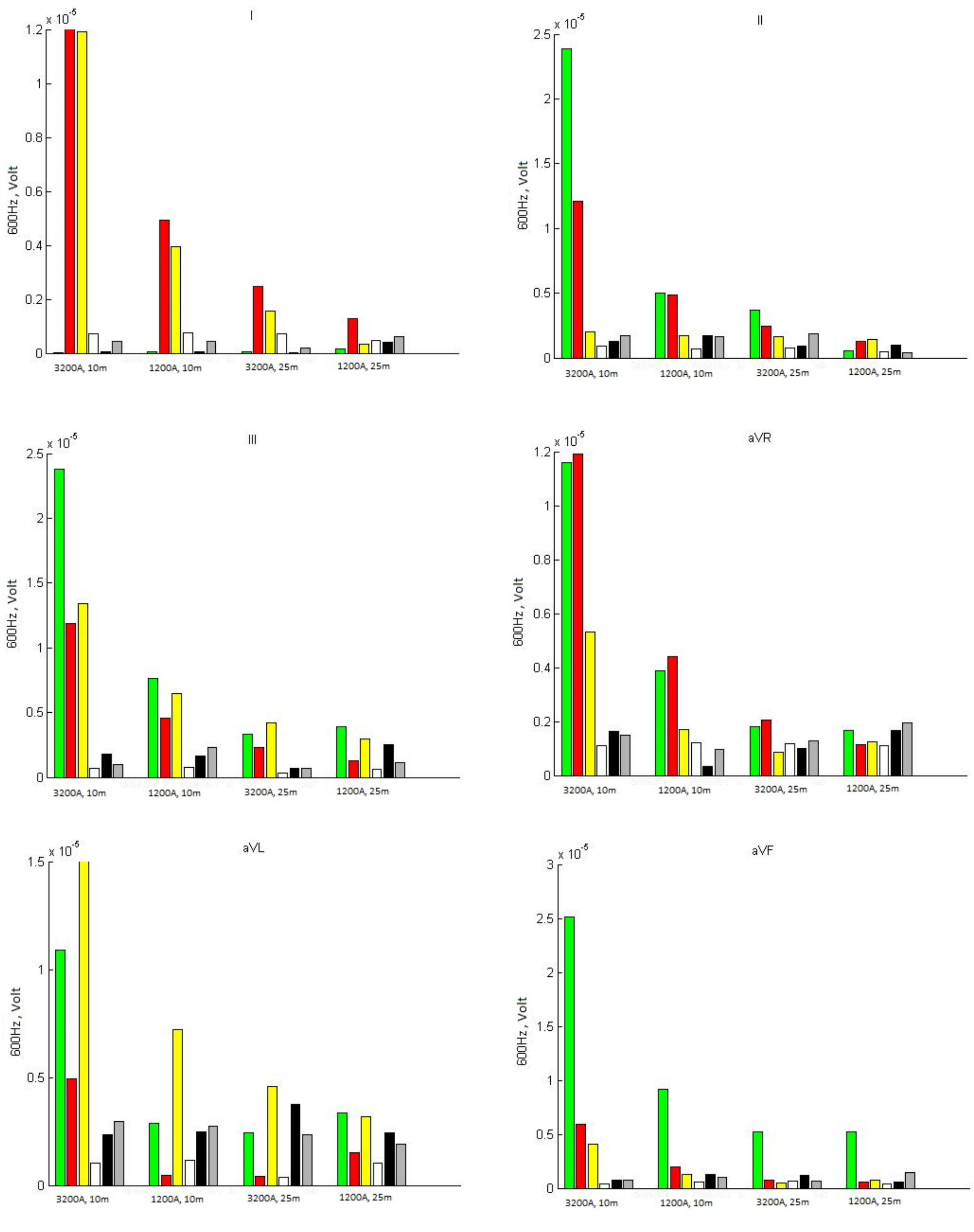


Figure 30: The magnitude of the ripple for all enclosed areas and and limb leads. The subplot shows the magnitude for a 600Hz (12-pulse rectification) interference. In each subplot the magnitude of the cases, 3200A at 10m, 1200A at 10m, 3200A at 25m and 1200A at 25m, are shown. The colors represents the wires enclosing an area.

5.4 Real life measurements

The measurements in Göteborg were made next to the tram track with the green and red wires taped to a box. This box were positioned parallel or vertical to the ground, at the distances of 10meters and 25meters, respectively. The area of the green wire is $0.72 \cdot 0.46m^2$ and the area of the red is $0.42 \cdot 0.46m^2$. For a signal with no interference, with the set ups as the one in Göteborg it has a background noise of a magnitude of 10^{-7}V for the frequencies 300Hz and 600Hz. It also showed that some disturbances occurred at frequencies where no energy should occur, when this setup was used.

For the measurements when the box was placed standing up and the green wire was enclosing the area, it showed that some but not all passing trams induced an interference in the ECG signals (Fig. 35 and Fig 36). For the signals of lead I and II, it showed that five out of eight passing trams correlates with peaks in the disturbance of the ECG signals. However in between some of these there are disturbances as large as the peaks. This indicates that there is a current passing on the tram track, even as no tram passes. Presumably this is due to a tram accelerating or decelerating at another location along the section. The signals III, aVR, aVL, aVF were all measured simultaneously, and it is clear that four and possibly five out of eleven trams clearly correlates with peaks in the magnitude of the interference.(Fig. 34, Fig. 35 and Fig 36) Some trams also show peaks a short time before or after their passing, though if these are correlated with the passing trams is unsaid. No real interference occur for the tram passing around the time 4.35s.

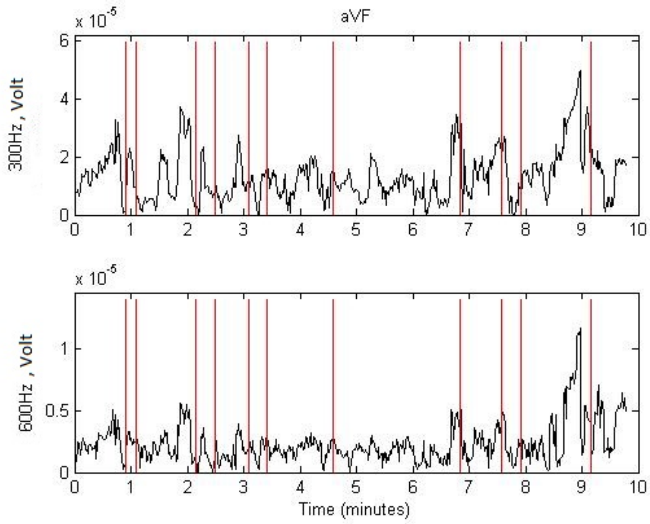


Figure 31: Spectral energy for the aVF lead, for the green wire enclosing and area for the box standing up at a distance of 10m from the tram track. The upper plot shows the energy for the 300Hz ripple, and the lower one shows the energy for the 600Hz harmonic. The lines shows the times there is a tram passing by the measurement site.

For the case where the box is laying parallel to the ground at 10m from the tram track with the green wire, signals I and II shows only one interference peak that coincides with the tram passing.(Fig. 37 and table 7 in Appendix) The first passing tram and the ones around 9 minutes has a peak close by them. The rest of the trams show no visible interference. Disturbance for these trams are as small or smaller than when there are no trams passing the measurement place. Interference when no trams are passing is also quite low.

The signals III, aVR, aVL and aVF (Fig. 32, Fig. 37 and Fig. 38) has clear interfering signals when three of the trams pass by the set up, the trams are the first and the two last ones. For the trams passing by around the time 3 to 4 minutes interference occurs though it is not on the exact time when the tram pass the measurement site. There are also a few trams which passes by but does not create a disturbance in the signal.

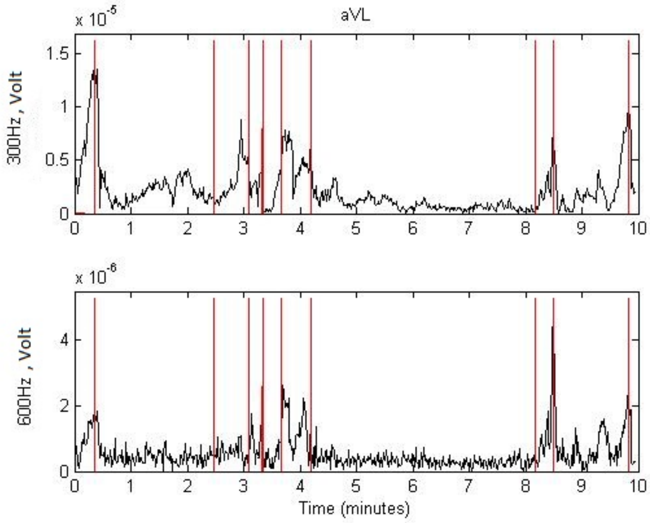


Figure 32: Spectral energy for the aVF lead, for the green wire enclosing and area for the box laying down at a distance of 10m from the tram track.The upper plot shows the energy for the 300Hz ripple, and the lower one shows the energy for the 600Hz harmonic. The lines shows the times there is a tram passing by the measurement site.

The case where the box were placed standing up, with the green wire enclosing an area, at a distance of 25m no clear indication of disturbance being correlated by the trams passing by are shown.(Fig 33, Fig 39 and Fig 40) Some peaks of disturbance can be seen close to passing trams, though peaks as high as these also exist where no tram passes. It is unclear if these are correlated to the trams. Some of the signals such as II, aVL and aVF have interferences in the order of 10^{-5}V.

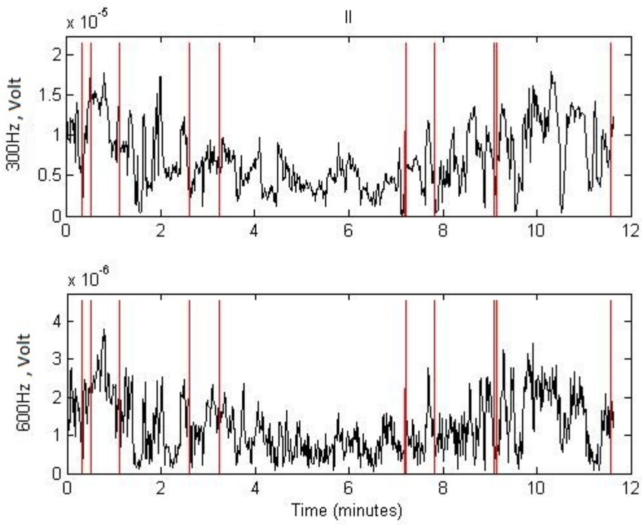


Figure 33: Spectral energy for the II lead, for the green wire enclosing and area for the box standing up at a distance of 25m from the tram track.The upper plot shows the energy for the 300Hz ripple, and the lower one shows the energy for the 600Hz harmonic. The lines shows the times there is a tram passing by the measurement site.

In the case for a box laying down with the green wire, no clear indication disturbance being correlated by the trams passing by can be spotted.(Fig. **??**, Fig. 41 and Fig 42) Some peaks of disturbance can be seen, they are spread over the spectrum and all are in the order of 10^{-6}V.

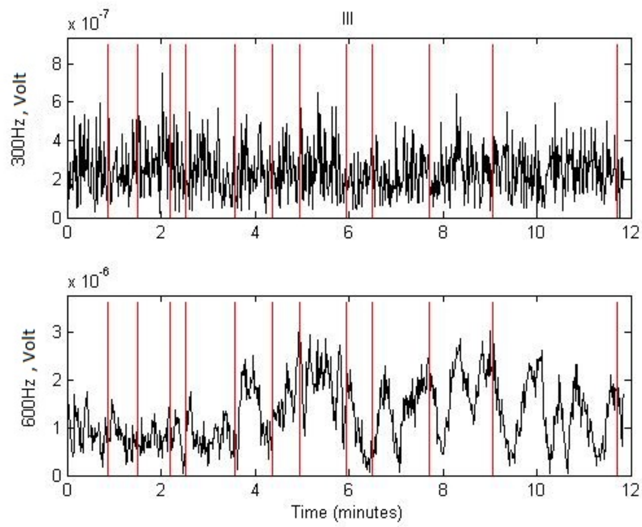


Figure 34: Spectral energy for the III lead, for the green wire enclosing and area for the box laying down at a distance of 25m from the tram track.The upper plot shows the energy for the 300Hz ripple, and the lower one shows the energy for the 600Hz harmonic. The lines shows the times there is a tram passing by the measurement site.

As the red wire were used to encircle an area and placed standing at a distance of 10m a probable correlation could be seen for the leads I and II for trams passing by at the times 37seconds and 1.36 minutes.(Fig. 35, Fig. 43 and Fig. 44) This correlation is not a clear one though. The other leads has no clear correlation between the disturbance in the ECG signals and passing trams.

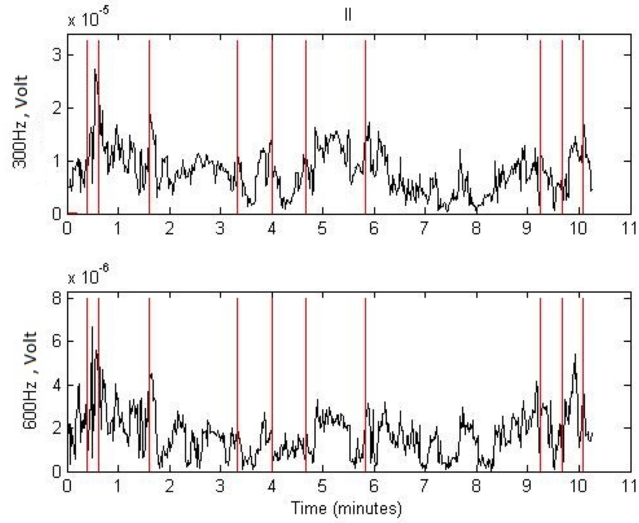


Figure 35: Spectral energy for the II lead, for the red wire enclosing and area for the box standing up at a distance of 10m from the tram track.The upper plot shows the energy for the 300Hz ripple, and the lower one shows the energy for the 600Hz harmonic. The lines shows the times there is a tram passing by the measurement site.

The last case considered was with the box parallel to the ground, with a red wire enclosing an area.(Fig. 36, Fig. 45 and Fig. 46) For this case the signals I and II shows a clear correlation between passing trams and interfering signal for all except two trams. In some of the clear cases the interference are starting a small time before the tram passes. For the signals aVR, aVL and aVF possible correlation between passing tram and interference can be seen for trams three of the eleven trams. No interference correlating to trams can be seen for III.

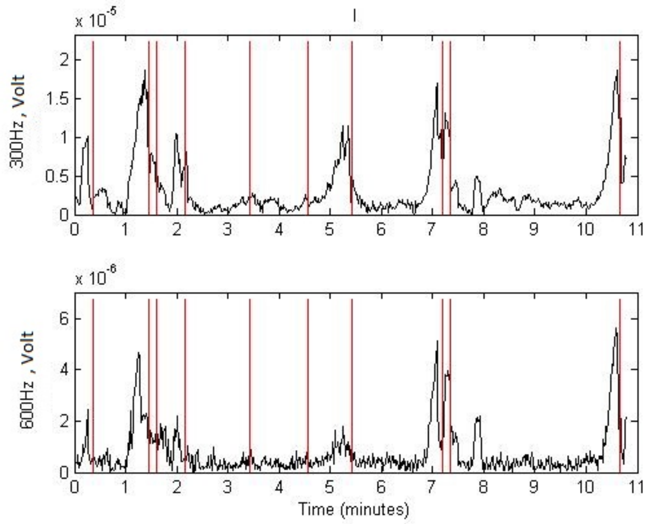


Figure 36: Spectral energy for the I lead, for the red wire enclosing and area for the box laying down at a distance of 10m from the tram track.The upper plot shows the energy for the 300Hz ripple, and the lower one shows the energy for the 600Hz harmonic. The lines shows the times there is a tram passing by the measurement site.

6 Discussion

6.1 Simulations

The different interfering cases occurring in ECG signals from a tramway passing by the hospital can clearly be seen affecting the signals in different ways. From the simulation it is clear that an accelerating or decelerating tram have no real effect on the signals, which were also concluded in the report by Dick van Beekum.[2] This is likely due to the slow decrease in magnetic field, though an accelerating tram would induce signals in the frequencies below 20Hz, which wouldn't be filtered by the monitor.

Current break between the tram and the overhead caternary will in the case with an amplifier and oscilloscope induce an interference in the signal. This signal will show up as a peak in the ECG and whether or not a possible disturbance of the interpretation is made is disputable. Since there is only a peak in the case of the oscilloscope, it is questionable if this signal is blocked by the filter in the monitor or if the signal used might have had a slight difference in amplitude between these two measurements. There might also have been a difference in the size of the enclosed area, as the measurements with monitor and oscilloscope were made at different times and the setup where made anew every time new measurements had to be made.

Ripple of a 6-phase rectifier will induce quite large interference in ECG signals. A clear difference can be seen between the case with a monitor with a band pass filter for 0.05Hz to 150Hz and an oscilloscope where no filter exists. Signals simulated for a distance of 10meters showed quite large interference for the oscilloscope, however the monitor showed a much smaller interference. The difference between these are likely due to the filter, however not all signals above 150Hz will be totally blocked by the filter, why an interference of 300Hz is still visible, but none around 600Hz. Measurements with the oscilloscope shows large interferences even for the harmonic at 600Hz. A 12-pulse rectification measured with the monitor shows a signal with a magnitude of the signal at the interfering frequencies that is in the order of the background noise, which might be due to the filter blocking the signal out in these cases. 12-phase rectification induced signals which are quite large into the oscilloscope set up, but whether if they affect the interpretation of the signal is debatable. Whether AC ripple in a DC signal might actually affect ECG interpretation is not clear as most interesting ECG measurements are between 0-150Hz. Though there are some cases, where higher frequencies might be used, for example in high frequency ECG , in this case the signals investigated are between 150-250, in which case 300Hz is outside of the range. However, these methods might develop into using higher frequencies in which case a ripple of 300Hz or 600Hz might be a problem.

The interference magnitude for different leads are varying depending on which wire enclose the area. It is clear that the wires green, red and yellow induced the most current, which might be due to these possibly being main factors in the transformation of EASI leads to representing limb leads. The green wire is in most cases the one inducing most interference and that might be due to a larger area. In a real life measurement, more than one of these wires might enclose an area where interference can be induced and might induce a larger or smaller interference in the signals. The angle between the field and wires might also change in real measurements, as the experiments tried to maximize the field. These signals might not be as large when measuring inside a building, as the simulations are made without considering any walls or buildings that might decrease the strength of the magnetic field. The magnitude of the signal might have been somewhat incorrect as the distances were measured by hand and the magnet were moved between measurements. The magnet used to simulate the field did distort the signals somewhat in the case with the rectified signal, and a signal where only a single rectification occurred were used(Fig. 18). This might have affected the interference of the rippled compared to a signal in real life, where full wave rectification is used, though it still possessed the desired frequencies and its harmonics.

6.2 Measurements in Göteborg

The measurements in Göteborg where made close by the track at a distance of approximately 10meters and 25meters, with the box standing up and laying down with the wires parallel to the ground, where the measurement site was horizontal in relation to the tramway. Measurements also included two cases where the red and the green wire enclose an area. In these measurements there exists some cases where a clear correlation between a passing tram and a peak in the spectral energy for the 300Hz and in 600Hz frequencies can be seen. In some cases there might be an interference around the time before or after the tram passes. The inexact correlation might be due to not registering the exact second the tram passed by the set up. Interference is most obvious for the box laying down, since when the box is standing up the interference is larger even when no tram passes. This might be due to a larger field in the z-direction, the direction away from the tram towards the measurement site, and might induce an interference even when stray currents might be traveling on the track. However, not every tram will show an interference, there are clear cases where trams pass by without any clear interference at all in the signals. The cause of this has to be unsaid, but might be due to the tram using only a fraction of its maximum current. There are even cases where no tram passes and an interference can be seen, though the interference is in general large when a tram passes by. The case with interference when no tram is present might be due to returning currents or an accelerating or decelerating tram at an other location along the section. As there sometimes is a disturbance before the tram arrives might be due to the case that the current on the over head canternary will be on the whole section not only where the tram is.

The case with no interference whatsoever are the ones that are peculiar, a reason for that might be as stated earlier that the trams are not using as much current, though there should still be some disturbance from the current on the wire. As measurements were made it can be seen that the largest interference is in the one for the green area, which would be the logical case as that one produces the larger area. The maximum interferences detected are in the order of the interference measured from the experiment simulating the maximum current 3200A of the tram system, which has a magnitude of 10^{-5}V at a distance of 10meters. The results indicate that there will be disturbances at the order of 10^{-6}V in the leads at 25meters and in the case for the II lead with a green box standing up, the disturbance reach 10^{-5}V. The background noise for both 300Hz and 600Hz is in the order of 10^{-7}. Whether if this interference is large enough to affect the detection of heart disorders is questionable, as the frequencies lay outside the heartbeats frequencies.

Investigating the signal for other disturbances than ripple showed no real interference, even if at least one tram stopped and accelerated past the site of the set up. The case with contact loss were likely not present in the measurement since no sparking could be seen from any passing trams, as that is the case which lead up to a current break.

The set up for this measurement introduced some few disturbances from the DC to AC converter, which could be seen some frequencies above 100Hz, in between 150Hz and 200Hz and a few frequencies above 200Hz. These signals does most likely occur due to aliasing of higher frequencies occurring as the converter, converts the current. These signals might not interfere with the result as these signals are at frequencies which are not of importance to this measurement. The converter might has introduced disturbances at lower frequencies than the one registered, which might be disguised by the frequencies of the heart signal. So there might be a small fault in whether or not there is any interference from other cases than the ripple, which might be disguised by this.

All measurements have been made with a maximized area to try and induce as large an interference as possible, though that might not be the real case. In a real life measurement the area might be smaller or larger depending on how the wires are placed onto the body surface and if a it is considered to make the area as small as possible. When measuring on a patient more than one wire might create an area, why a larger interference might be possible when measuring on the patient. The area has been maximized according to the interference in the z-direction when simulating, as this interference is the largest from the tracks. If the areas enclosed by the wires could be directed in another direction than the z-direction the interference could be lowered. There is also the case that these measurements have been made in an environment where no walls or buildings have been included, why a real interference inside the hospital might be lower than the one in this report, due to walls and buildings shielding against the magnetic field. However, a low frequency magnetic field is hard to shield why the measured interference probably is similar to a real measurement. All measurements are made in a worst case scenario, though in a real measurements the interference might be as high, depending on the causes of interference presented above and if it is taken into consideration to lower the interference. Should there occur higher frequencies than are possible to register with the samplerate of the monitor, these might be registered as lower frequencies in the ECG signals due to aliasing, and might affect the interpretation.

It is likely that some of the interferences occurring from the tramway might interfere with the interpretation. The ones which would interfere are ripple and current break, where the large ripple from a 6 pulse rectification and short distances might occlude much of the information. A small ripple might make it harder to interpret atrial fibrillation as it could shield the small waves occurring due to the fibrillation. As some ECG measurements such as high frequency ECG are very close to the the ripple frequency of 6 pulse rectification, this might disturb the signals. With these problems in consideration a 12 pulse rectification might be the better choice. Considering the current break a peak similar to the peak from a pacemaker occurs, why this might disturb the measured signals and therefore it could be beneficial to have this in mind when measuring ECG on a person which has a pacemaker.

If there exists any immunity level, which the interference should be below, as indicated by Dick van Bekkum, is questionable. As the importance case to determine is whether or not the heart rate is accurate. It is clear that some interference might disturb the ECG signals, why it is important that the personnel measuring the ECG makes the area enclosed by the wires as small as possible and measures the ECG as far away from the tramway as possible. It would also be beneficial if the tramway were designed for a 12 pulse rectification, since the interference would become very small. Though if the interference is such that important information is lost is a case which have to be determined from a medical view.

7 Conclusions

ECG signals will be affected by the magnetic field from trams. There is a clear interference in the signals from the AC ripple of the DC current. This interference can be seen for the signals both in the experiments an the measurements in real life, where the signal will decay with distance, though some interference will still occur at 25meters. The correlation with passing trams and interference are seen for some of them, when some did not interfere with the signal at all. The interference at 10meters could be clear and large at times. An interference from accelerating and decelerating trams are not inducing any visible interference in the signal. The case with a contact break could in experiments show interference, however no such interference could be seen in Göteborg, why measurements to see if this really do interfere in real life would have had been done when the weather conditions are such that break easily occurs. The buildings further away than 25meters will probably not be affected by the tram, however the ones closer than 10meters will probably be affected. It is also concluded that the interference can be minimized if the area created by the wires is kept small. Whether if these signals will interfere in a manner which will hinder the measurement and interpretation of the signal are a question that has to be answered by someone used to interpret ECG signals.

References

[1] Längs Linjen. *Spårvagn Lund*. URL: http://www.sparvaglund.se/sv/langs-linjen/ (visited on 11/03/2014).

[2] van Bekkum Dick. "EMC – Time varying electromagnetic fields 1". In: (2014).

[3] Laguna Pablo Sörnmo Leif. *Bioelectrical signal processing in cardiac and neurological applications*. 1st ed. Elsevier Academic Press, 2005. ISBN: 978-0-12-437552-9.

[4] Stran Kevin T. Widmaier Eric P Raff Hershel. *Vanders Human Physiology: The mechanism of body functions*. 13th ed. McGraw-Hill Higher Education, 2014. ISBN: 978–0–07–337830–5.

[5] Jacobsson Bertil. *Medicin och teknik*. 5th ed. Studentlitteratur AB, 2006. ISBN: 91-44-04760-6.

[6] Wikipedia. *QRS-complex*. URL: http://en.wikipedia.org/wiki/QRS_complex#mediaviewer/File:SinusRhythmLabels.svgl (visited on 11/03/2014).

[7] Schlegel Todd T Trägårdh Elin. *High-freqency ECG*. URL: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060056493.pdf (visited on 11/19/2014).

[8] Joakim Alfredsson Piotr Szamlewski Jonas Schwieler Eva Swahn. *EKG-tolkning, En klinisk guide*. URL: http://distriktslakare.com/wp-content/uploads/ekg-boken-fran-ekgtolkning_se.pdf (visited on 12/08/2014).

[9] Olle Pahlm Sörnmo Leif. *Elektokardiologi, klinik och teknik*. 1?? Studentlitteratur AB, 2006.

[10] Philips. *Bruksanvisning IntelliVue patientmonitor MP20/30, MP40/50, MP60/70/80/90*.

[11] Hamnerius Yngve. *Elektriska och magnetiska fält från spårvägstrafik*. May 2012.

[12] Edstarnd Jacob. "Calculation method for powering a tramway network". MA thesis. Chalmers univeriesty of technology, 2012.

[13] Brümmer Lars Schiöth Mattias. *Handledning för spårvägsplanering i Skåne*. Apr. 2011. URL: http://www.sparvaglund.se/PageFiles/364/Handledning-f%C3%B6r-sp%C3%A5rv%C3%A4gsplanering-i-Sk%C3%A5ne-2011-04.pdf (visited on 10/10/2014).

[14] Vår flotta. *Göteborgsspårvagnar*. URL: http://www.goteborgssparvagar.se/om-oss/var-flotta/ (visited on 07/11/2014).

[15] Caglar Erol. *Personal communication, Göteborgsspårvagnar*.

[16] Williams Tim. *EMC for Product Designers*. 4th ed. Elsevier Ltd, 2007. ISBN: 987-0-75-068170-4.

[17] Weber Ernst. *ELECTROMAGNETIC FIELDS, Theory and Applications, Volume I Mapping of Fields*. 3rd ed. John Wiley and Sons, 1950.

[18] Misakian Martin. "Equations for the Magnetic Field Produced by One or More Rectangular Loops of Wire in the Same Plane". In: (2000).

[19] Griffiths David J. *Introduction to Electrodynamics*. 3rd ed. Pearson Education Inc, 2008. ISBN: 0-13-919960-8.

[20] W.Ott Henry. *Noise reduction techniques in electronic systems*. 2nd ed. John Wiley and Sons, 1988. ISBN: 0-471-85068-3.

[21] Inc. National Technical Systems. *Immunity Testing (Susceptibility Testing)*. URL: http://www.elliottlabs.com/services_emc_immunity.htm (visited on 09/03/2014).

[22] Freznel Jr Louis E. *Electronics Explained: The new systems approach to learning electronics*. 1st ed. Elsevier Inc, 2010. ISBN: 978-1-85617-700-9.

[23] Stanley William D. *Electronic devices, Circuits and Applications*. 1st ed. Prentice-Hall, 1989. ISBN: 978-0132489492.

[24] Fredriksen Thomas M. *Intuitive Operational amplifiers*. Revised. McGraw-Hill Book Company, 1988. ISBN: 0-07-021967-2.

[25] Analog devices. *Instrumentation amplifier*. URL: http://www.analog.com/static/importedfiles/design_handbooks/5812756674312778737Complete_In_Amp.pdf (visited on 10/11/2014).

[26] Wikipedia. *Instrumentation amplifier*. URL: http://en.wikipedia.org/wiki/Instrumentation_amplifier (visited on 10/11/2014).

[27] Gustafsson Mats Sjöberg Daniel. *Kretsteori, ellära och elektronik*. 4th ed. Institutionen för elektro- och infotmationsteknik, LTH, 2011.

[28] Siemens. *Sitras Rec, Diode rectifier for DC traction power supply, product informarion.*

[29] Johansson Jimmy. "Integration of NovoSense CardioBase and existing patient monitoring system". MA thesis. Lund University, 2012.

8 Appendix

8.0.1 Real life measurements

8.0.2 Distance of 10m and the green wire with a standing box

For the leads I and II trams 822, 852,352, 310 and 375 correlates with peaks and for III, aVR, aVL, aVF the trams 336, 846, 333, 343 and possibly 444 correlates with peaks.

Time (min.sec)	Direction	Tramline	Tram number	Model
0.55	Botaniska Trädgården	8	444	M32
1.05	Göteborg	8	336	M31
2.09	Botaniska Trädgården	7	846	M29
2.30	Stopped at location	2	740	M28
3.05	Göteborg	7	453	M32
3.25	Botaniska Trädgården	2	843	M29
4.35	Botaniska Trädgården	1	718	M28
6.50	Botaniska Trädgården	7	333	M31
7.35	Göteborg	8	434	M32
7.55	Botaniska Trädgården	8	717	M28
9.10	Botaniska Trädgården	8	366	M31

Table 4: The passing trams for the leads aVR/avL/aVF/III

Time (min.sec)	Direction	Tramline	Tram number	Model
0.10	Göteborg	2	822	M29
1.25	Botaniska Trädgården	2	741	M28
2.15	Botaniska Trädgården	7	852	M28
4.15	Stopped at locationn	1	849	M28
6.05	Botaniska Trädgården	8	352	M31
7.44	Botaniska Trädgården	2	843	M29
8.05	Not Registered	8	310	M31
9.30	Not registered	7	375	M31

Table 5: The passing trams for the leads I/II

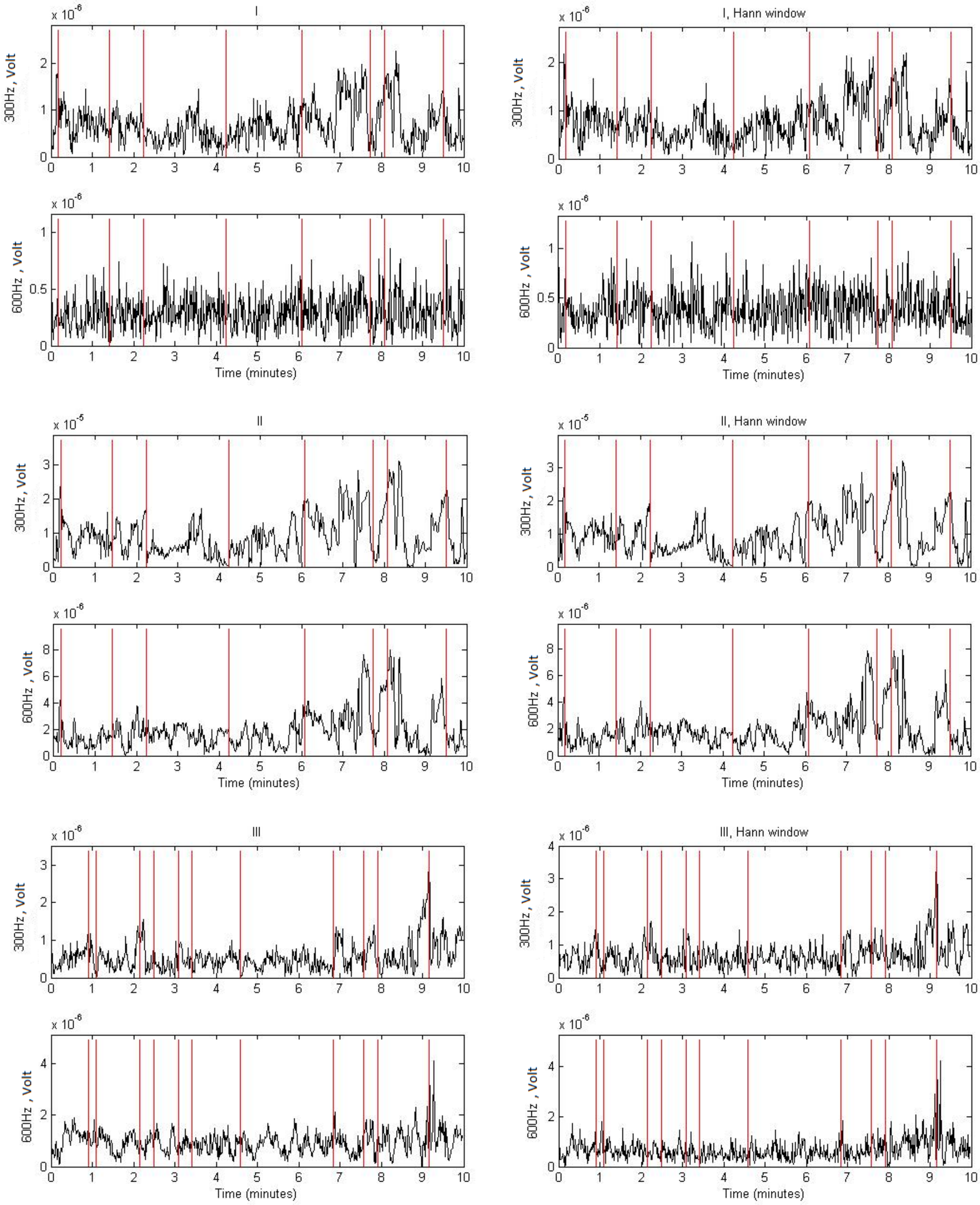


Figure 37: Spectral energy for signals I, II and III, at frequencies 300Hz and 600Hz

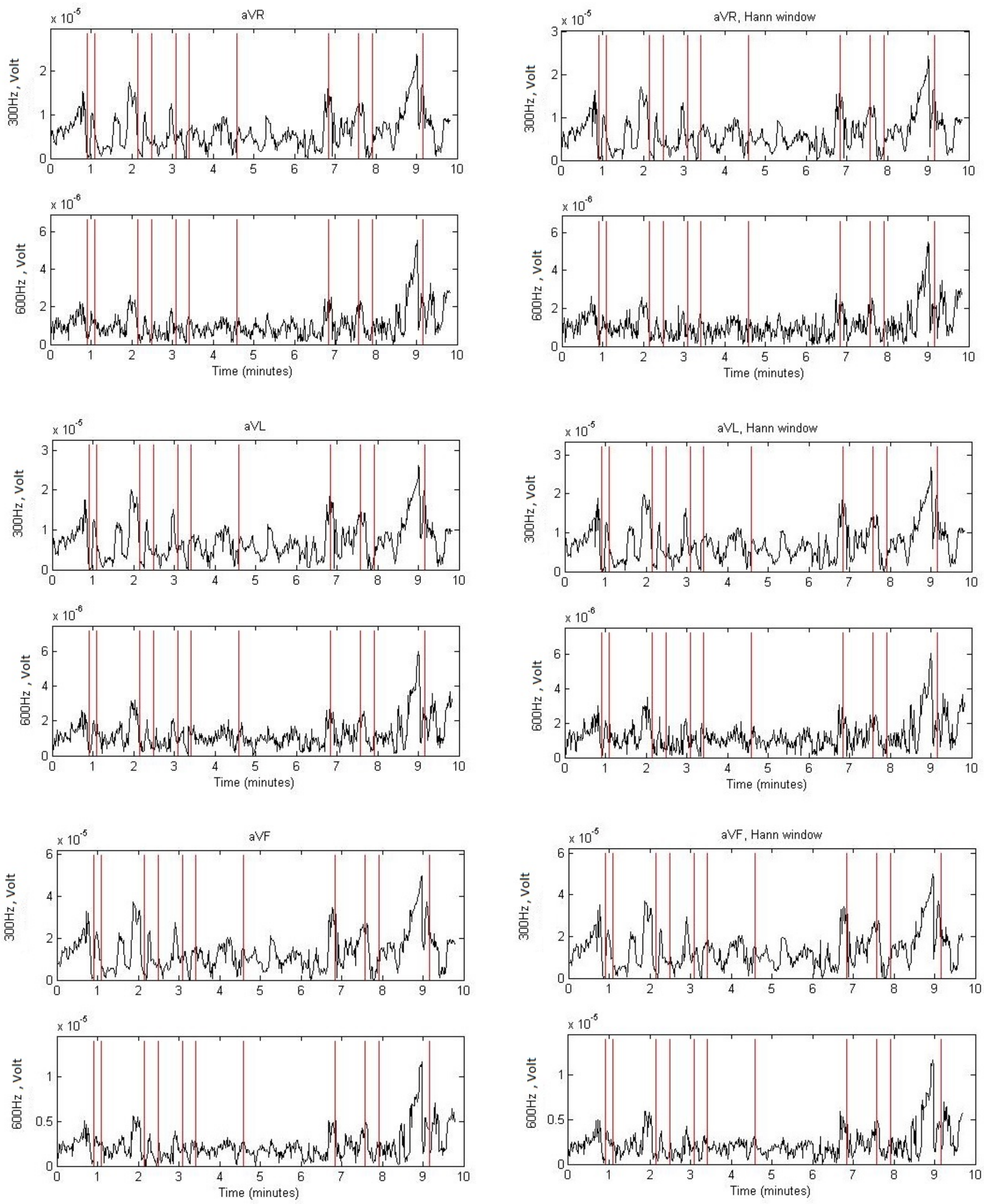


Figure 38: Spectral energy for signals aVR, aVL and aVF, at frequencies 300Hz and 600Hz

8.0.3 Distance of 10m and the green wire with a laying box

For the leads I and II trams 338 correlates with peaks and for III, aVR, aVL, aVF the trams 457, 435 and - and possibly 835 correlates with peaks.

Time (min.sec)	Direction	Tramline	Tram number	Model
0.21	Botaniska Trädgården	8	457	M32
2.28	Göteborg	2	741	M28
3.05	Botaniska Trädgården	2	835	M29
3.20	Göteborg	8	380	M31
3.40	-	1	371	M31
4.12	-	7	357	M31
8.10	-	1	315	M31
8.30	-	8	-	-
9.50	-	7	435	M32

Table 6: The passing trams for the leads aVR/aVL/aVF/III

Time (min.sec)	Direction	Tramline	Tram number	Model
2.35	Göteborg	2	821	M29
3.30	Göteborg	9	208	-
3.55	Botaniska Trädgården	1	807/722	M29/M28
4.35	Göteborg	7	333	M31
5.00	Göteborg	1	718/761	M28
7.15	Botaniska Trädgården	7	338	M31
9.00	Göteborg	8	366	M31
9.27	Botaniska Trädgården	8	447	M32
9.37	Göteborg	1	835/704	M29/M28

Table 7: The passing trams for the leads I/II

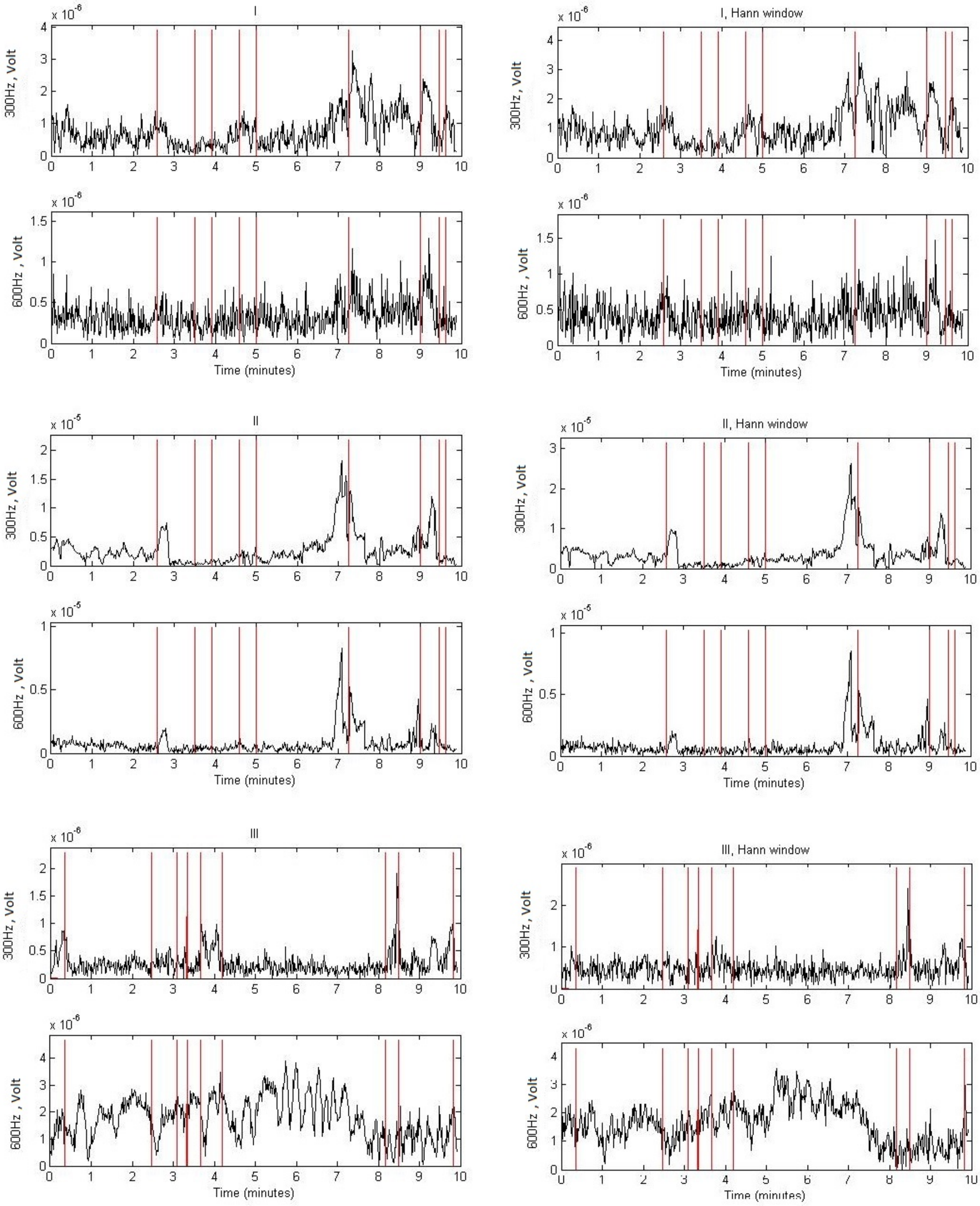


Figure 39: Spectral energy for signals I, II and III, at frequencies 300Hz and 600Hz

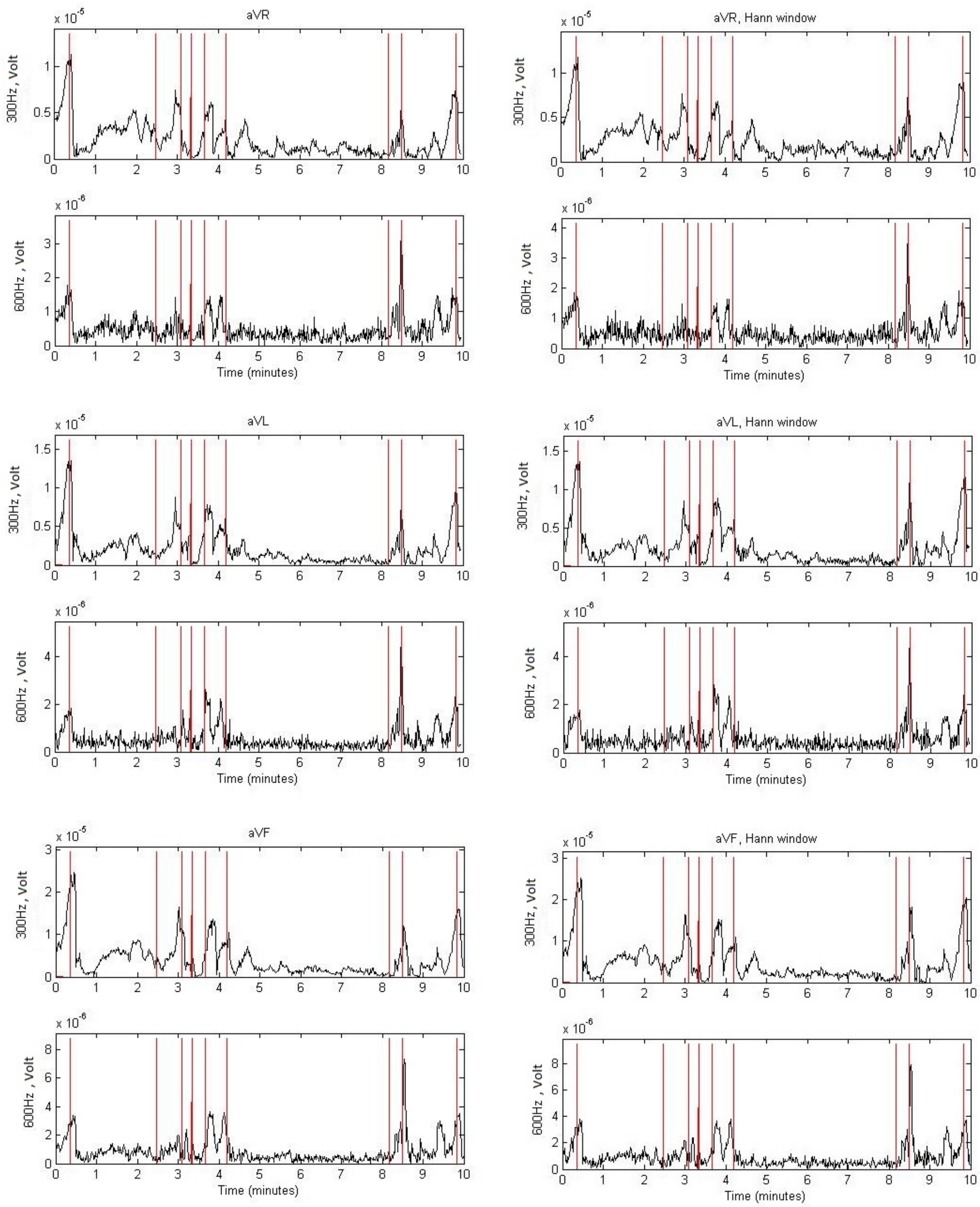


Figure 40: Spectral energy for signals aVR, aVL and aVF, at frequencies 300Hz and 600Hz

8.0.4 Distance of 25m and the green wire with a standing box

No clear interference exists for any trams.

Time (min.sec)	Direction	Tramline	Tram number	Model
0.36	Göteborg	1	455	M32
0.55	Botaniska Trädgården	7	742	M28
2.30	Botaniska Trädgården	8	327	M31
5.30	Botaniska Trädgården	2	738/745	M28
5.50	Göteborg	8	457	M32
6.25	Göteborg	2	827/705	M29/M28
6.37	Botaniska Trädgården	1	850/734	M29/M28
7.00	Göteborg	7	329	M31
9.55	Göteborg	1	371	M31

Table 8: The passing trams for the leads aVR/aVL/aVF/III

Time (min.sec)	Direction	Tramline	Tram number	Model
0.19	Göteborg	2	814/726	M29/M28
0.30	Botaniska Trädgården	8	321	-
1.07	Göteborg	8	362	M31
2.36	Göteborg	7	4355	M32
3.15	Botaniska Trädgården	1	826/727	M29/M28
7.12	Göteborg	1	807/722	M29/M28
7.50	Botaniska Trädgården	7	751/854	M28/M298
9.05	Göteborg	7	738	M28
9.08	Botaniska Trädgården	8	378	M31
11.35	Göteborg	2	740	M28

Table 9: The passing trams for the leads aVR/aVL/aVF/III

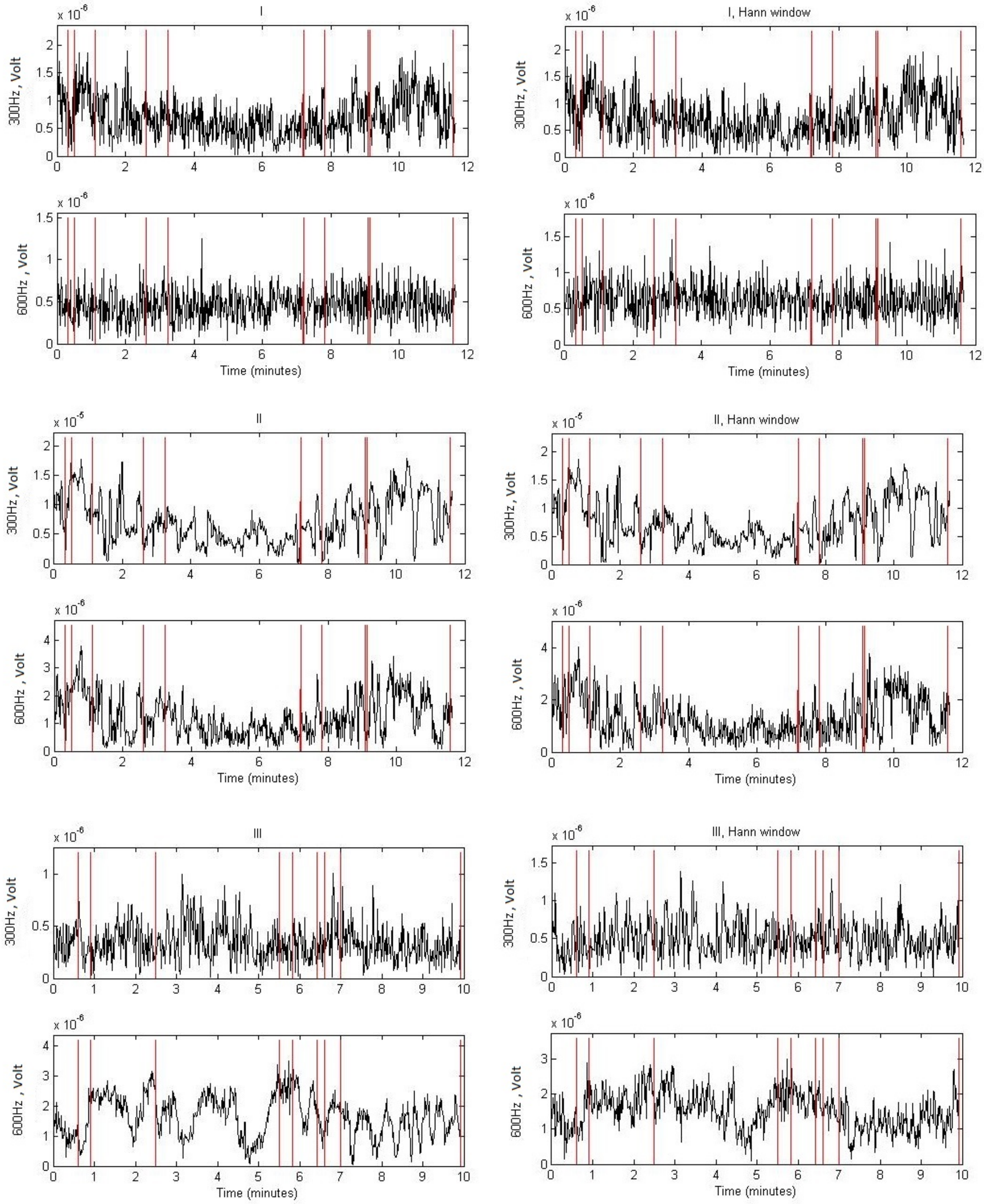


Figure 41: Spectral energy for signals I, II and III, at frequencies 300Hz and 600Hz

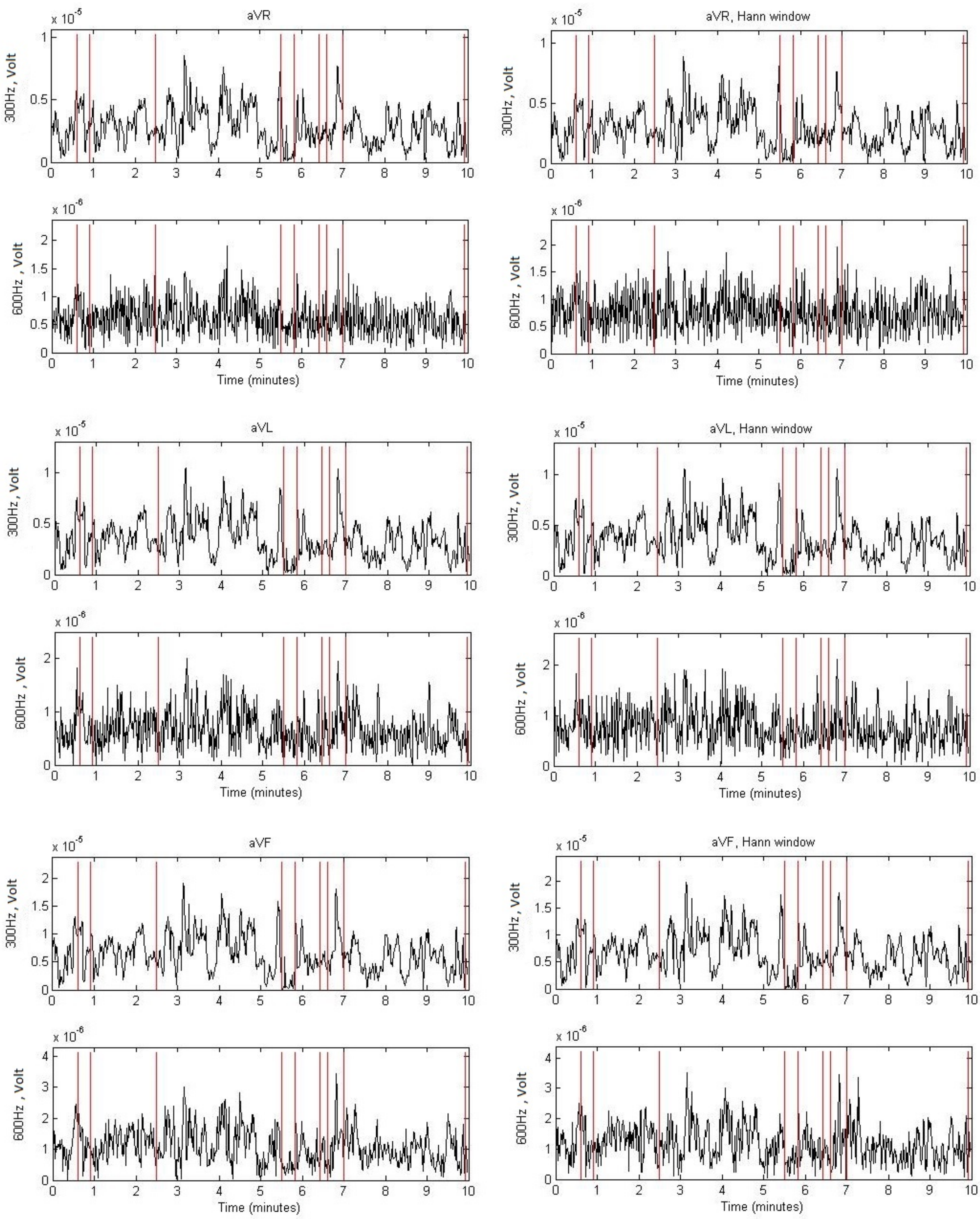


Figure 42: Spectral energy for signals aVR, aVL and aVF, at frequencies 300Hz and 600Hz

8.0.5 Distance of 25m and the green wire with a laying box

No clear interference exists for any trams.

Time (min.sec)	Direction	Tramline	Tram number	Model
0.52	Botaniska Trädgården	7	372	M31
1.30	Göteborg	8	447	M32
2.12	Botaniska Trädgården	8	334	M31
2.32	Botaniska Trädgården	7	338	M31
3.35	Göteborg	1	308	M31
4.22	Göteborg	8	458	M32
4.57	Göteborg	2	335	M31
5.57	Göteborg	7	763/729	M28
6.30	Botaniska Trädgården	2	846	M29
7.42	Botaniska Trädgården	1	434	M32
9.03	Göteborg	1	341	M31
11.42	Göteborg	8	367	M31

Table 10: The passing trams for the leads aVR/aVL/aVF/III

Time (min.sec)	Direction	Tramline	Tram number	Model
0.06	Göteborg	2	740	M28
0.18	Botaniska Trädgårdeng	1	849/759	M29/M28
0.49	Göteborg	7	742	M28
3.30	Botaniska Trädgårdeng	7	435	M32
5.17	Göteborg	1	856/734	M29/M28
6.20	Botaniska Trädgården	7	843	M29
7.15	Göteborg	2	846	M29
7.35	Botaniska Trädgården	8	438	M32
7.50	Göteborg	8	321	M31
8.48	Botaniska Trädgården	1	707/766	M28

Table 11: The passing trams for the leads I/II

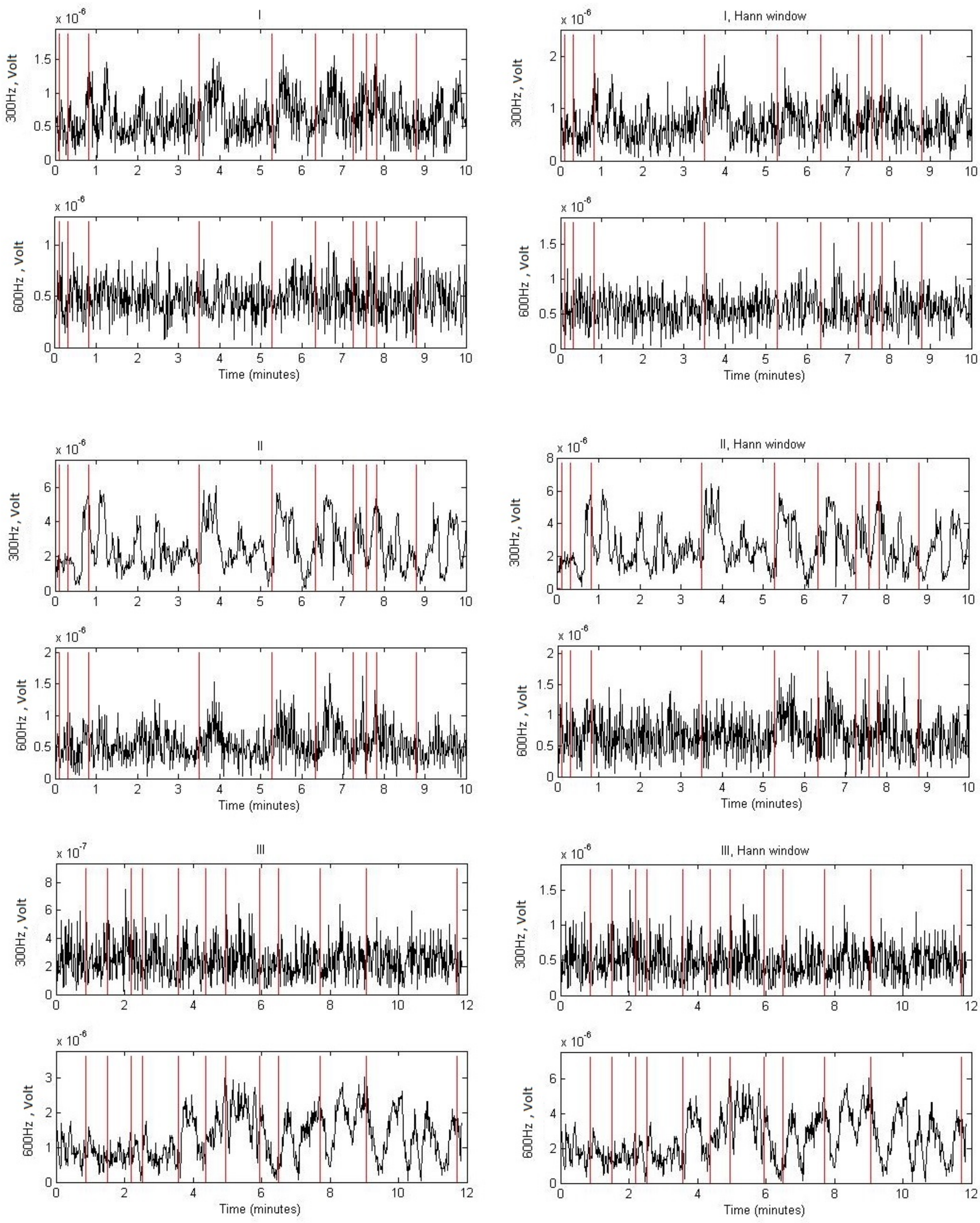


Figure 43: Spectral energy for signals I, II and III, at frequencies 300Hz and 600Hz

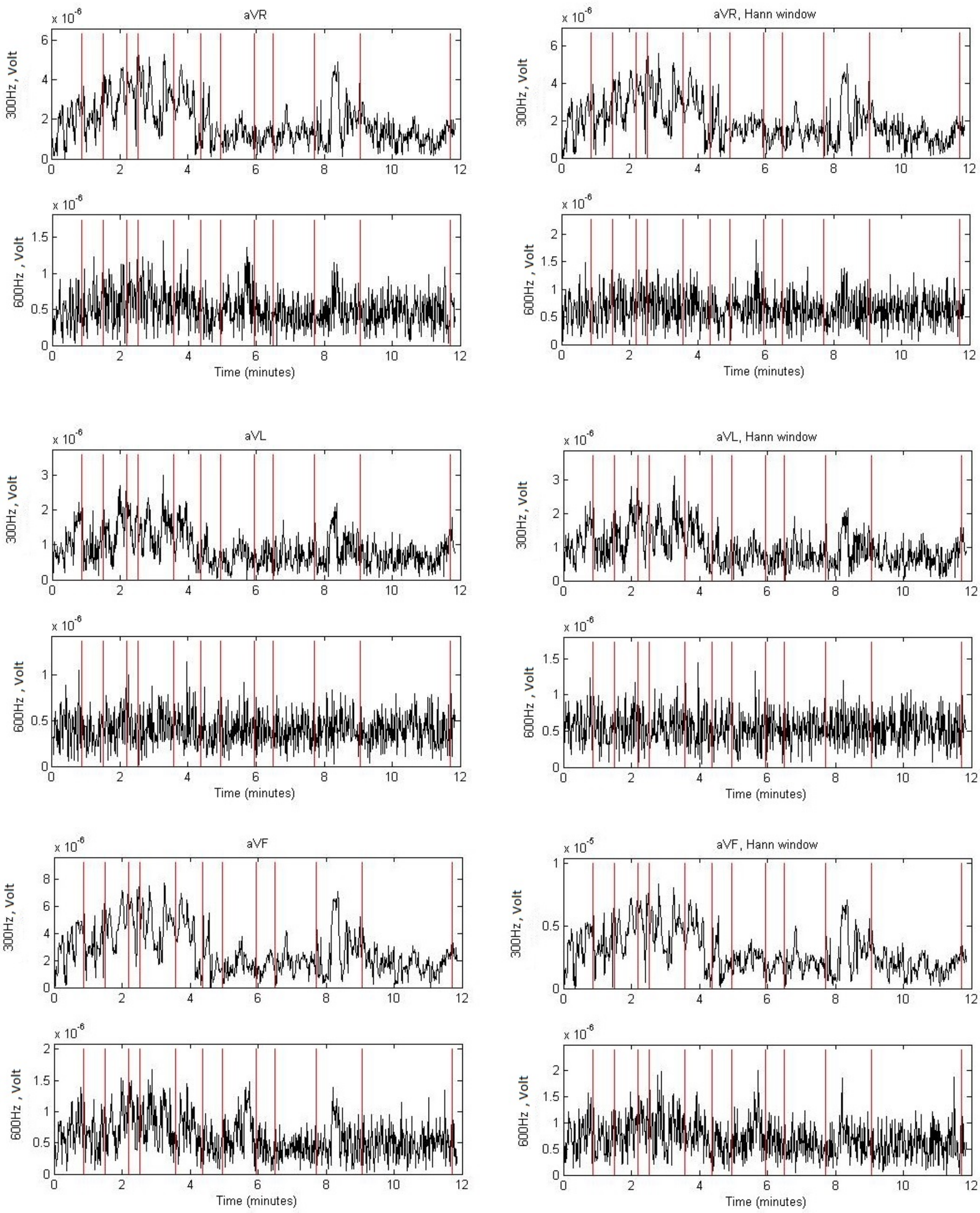


Figure 44: Spectral energy for signals aVR, aVL and aVF, at frequencies 300Hz and 600Hz

8.0.6 Distance of 10m and the red wire with a standing box

Signals I and II shows a probable correlation for the trams 821, 453. For the other signals no clear correlation can be seen.

Time (min.sec)	Direction	Tramline	Tram number	Model
1.53	Botaniska Trädgården	2	835/704	M29/M28
2.17	Göteborg	8	367	M31
2.37	Botaniska Trädgården	8	427	M32
3.00	Göteborg	2	741/752	M28
3.10	Botaniska Trädgården	1	454	M32
6.00	Göteborg	7	322	M31
8.16	-	1	849/759	M29/M28
10.40	Botaniska Trädgården	7	333	M31

Table 12: The passing trams for the leads aVR/aVL/aVF/III

Time (min.sec)	Direction	Tramline	Tram number	Model
0.23	Botaniska Trädgården	8	351	M31
0.37	Göteborg	2	821	M29
1.36	Göteborg	7	453	M32
3.20	Botaniska Trädgårdeng	5	703/768	M28/M29
4.00	Botaniska Trädgården	7	717/815	M28/M29
4.40	Botaniska Trädgården	1	455	M32
5.50	Göteborg	1	707/766	M28
9.15	Göteborg	2	835/704	M29/M28
9.40	Botaniska Trädgården	1	371	M31
10.05	Göteborg	8	376	M31

Table 13: The passing trams for the leads I/II

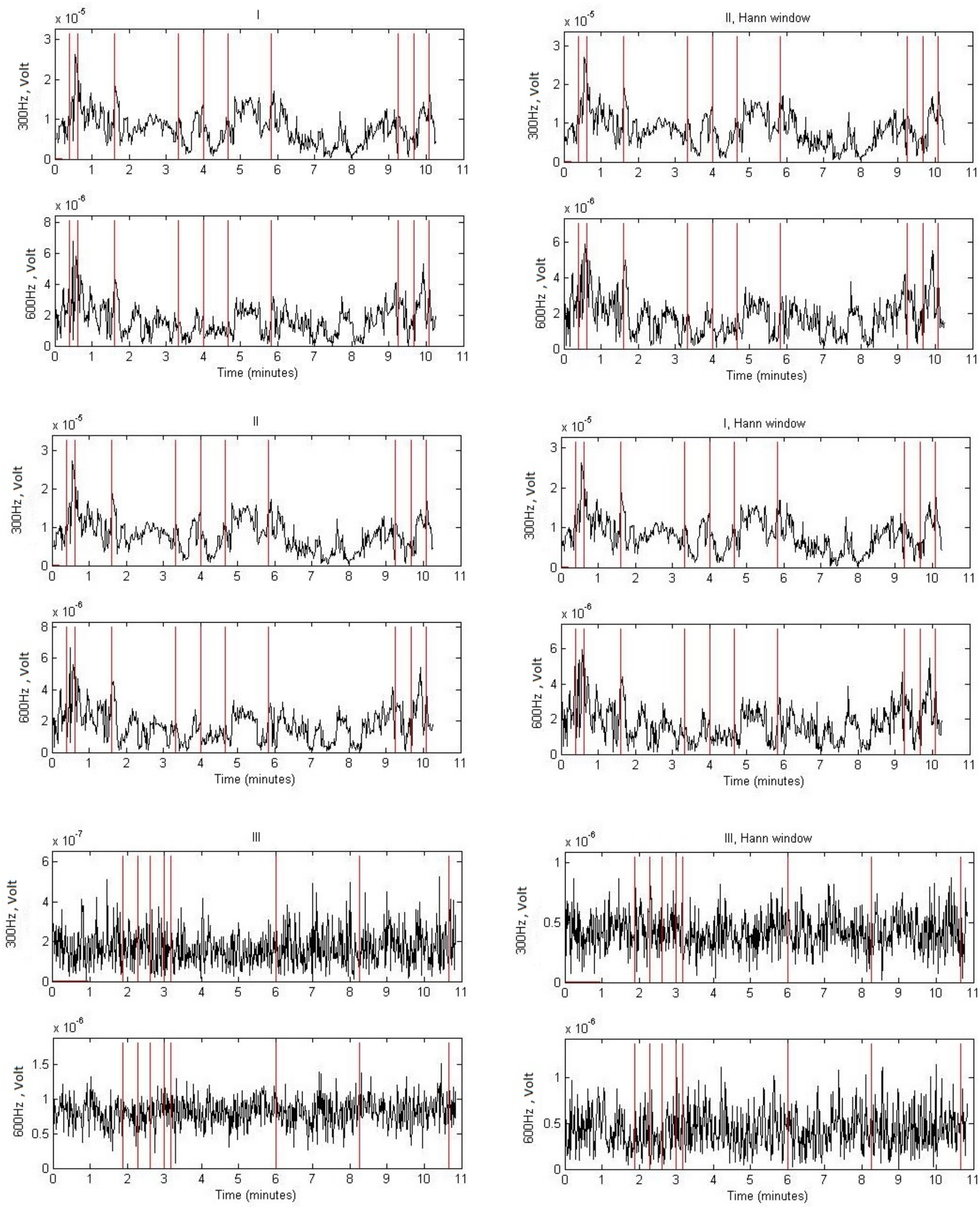


Figure 45: Spectral energy for signals I, II and III, at frequencies 300Hz and 600Hz

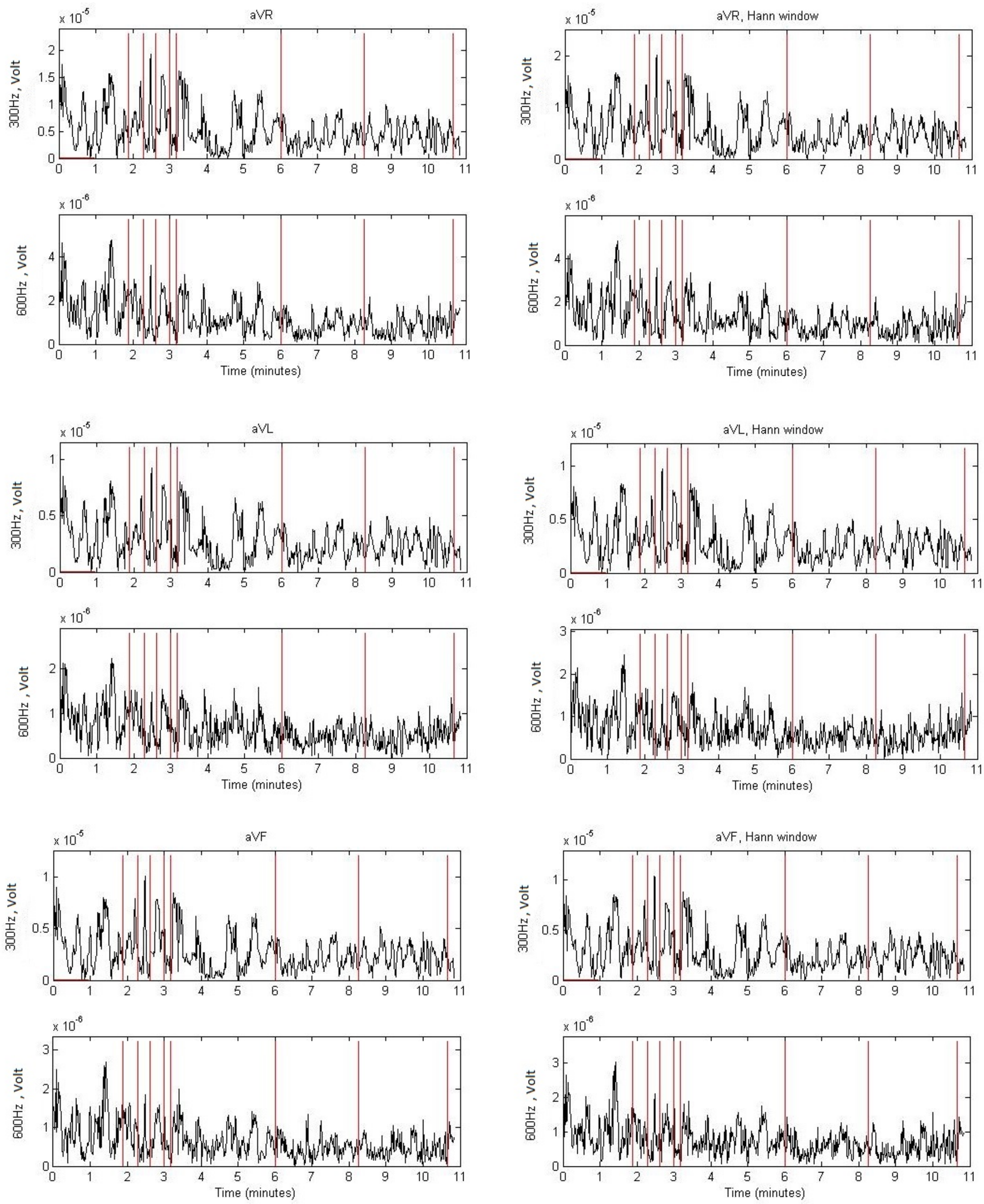


Figure 46: Spectral energy for signals aVR, aVL and aVF, at frequencies 300Hz and 600Hz

8.0.7 Distance of 10m and the red wire with a laying box

Signals I and II shows correlation for all trams except 827/705 and 427. The leads aVR, aVL and aVF shows correlation for trams 745/738, 335, 333 and 341. No interference correlating to trams can be seen for III.

Time (min.sec)	Direction	Tramline	Tram number	Model
0.29	Botaniska Trädgården	7	852/762	M29/M28
1.50	Göteborg	7	312	M31
3.10	Göteborg	1	313	M31
3.12	Botaniska Trädgården	2	726/814	M28/M29
5.26	Göteborg	2	402	M32
6.00	Göteborg	8	322	M31
6.50	Göteborg	7	375	M31
6.50	Botaniska Trädgården	8	428	M32
7.30	Botaniska Trädgården	1	807/722	M29/M28
9.30	Botaniska Trädgården	7	329	M31
10.20	Botaniska Trädgården	13	770	M28

Table 14: The passing trams for the leads aVR/aVL/aVF/III

Time (min.sec)	Direction	Tramline	Tram number	Model
0.22	Botaniska Trädgården	2	745/738	M28
1.27	Botaniska Trädgården	1	308	M31
1.36	Göteborg	1	454	M32
2.10	Botaniska Trädgårdeng	8	445	M32
3.26	BGöteborg	2	827/705	M29/M28
4.34	Göteborg	8	427	M32
5.25	Botaniska Trädgården	7	435	M32
7.12	-	2	335	M31
7.21	-	7	333	M31
10.40	Botaniska Trädgårdeng	1	341	M31

Table 15: The passing trams for the leads I/II

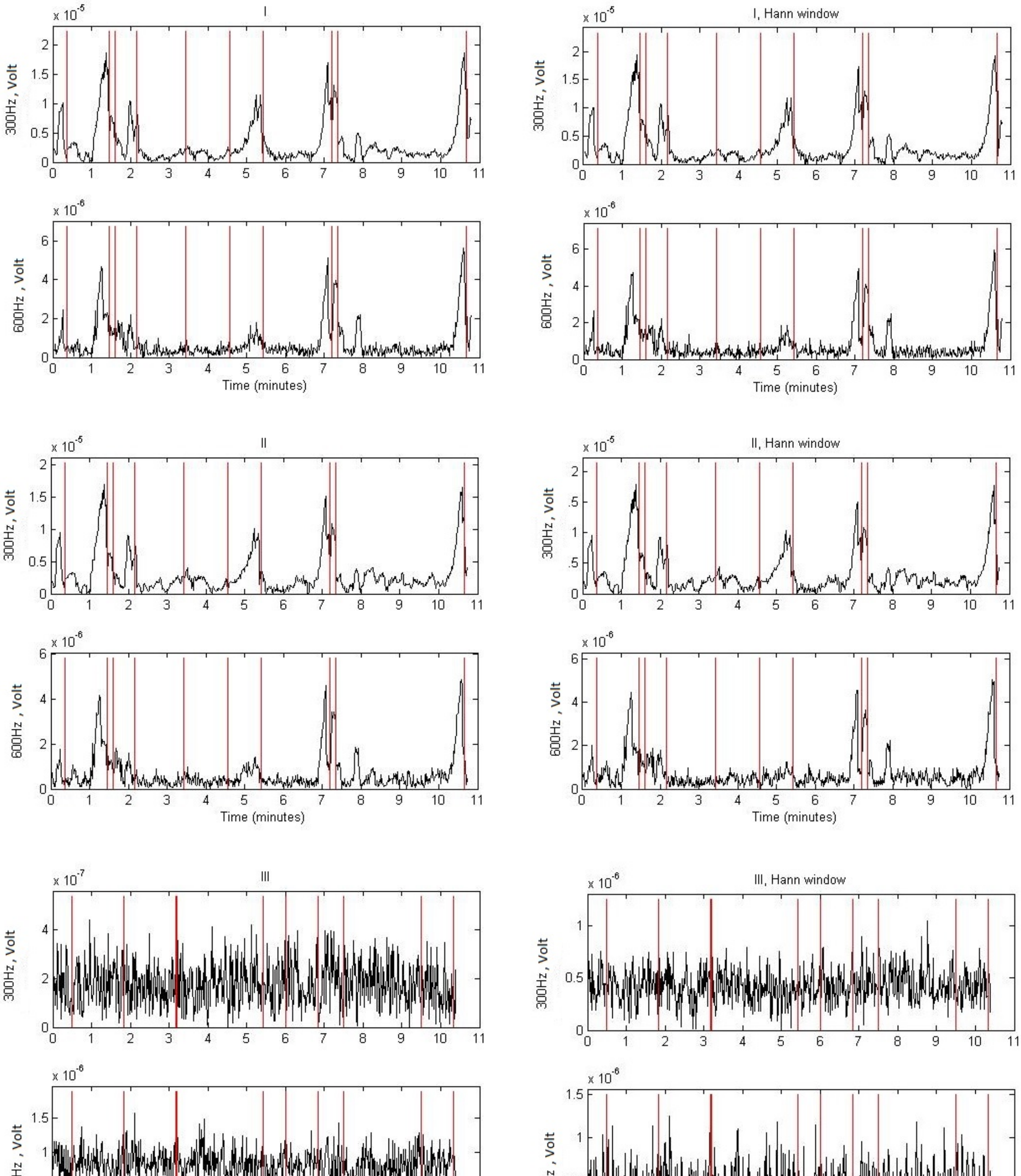


Figure 47: Spectral energy for signals I, II and III, at frequencies 300Hz and 600Hz

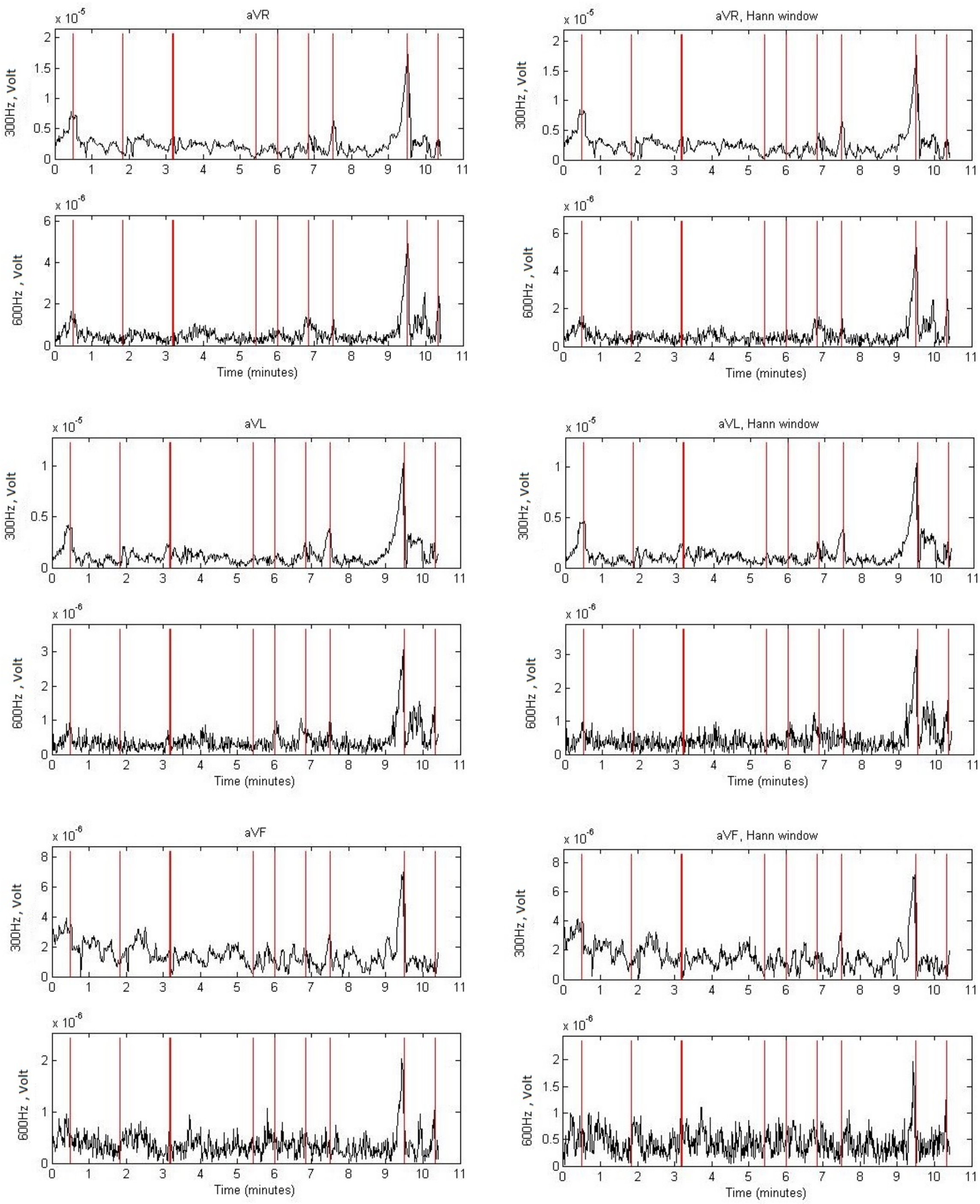


Figure 48: Spectral energy for signals aVR, aVL and aVF, at frequencies 300Hz and 600Hz