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Ph.D. THESIS

**INVESTIGATION OF ELECTRICAL TRANSIENT
CHARACTERISTICS FOR DIFFERENT GROUNDING SYSTEMS**

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Explanation
A	: Surge arrester exponential factor
E	: Step Voltage
h	: Height of the grid depth (m)
I	: Current in Amper
I_f	: Fault current
I_{aar}	: Current created during suppression of voltage
K_{seg}	: Voltage segment factor
P	: Soil resistivity
S_f	: Split factor
U_{aa}	: Reference operating voltage of surge arrester
Z_g	: Ground impedance

Abbreviation	Explanation
cur Ben	: Bentonite current
cur NG	: Natural enhancement material current
DWT	: Discrete Wavelet Transform
ERT	: Electrical Resistivity Tomography
EST	: Electrical Sounding Technique
FEM	: Finite Element Method
GEC	: Ground Enhancement Compound
GEM	: Ground Enhancement Material
GPR	: Ground Potential Rise
GS	: Grounding System
H	: Humidity level
HV	: High Voltage
LV	: Low Voltage
MOA	: Metal Oxide surge Arrester
MV	: Meduim Voltage
NA	: Not Available
NBS	: National Bureau of Standards

NBS	: National Bureau of Standards
NG	: Natural Ground
NGEM	: Natural Ground Enhancement Material
PKOC	: Palm Kernel Oil Cake
RRA	: Resistance Reduction Additive
VES	: Vertical Electrical Sounding
ZB	: The transient impedance of bentonite
ZE	: The transient impedance of normal soil
ZN	: The transient impedance of proposed natural enhancement material



ÖZET

DOKTORA TEZİ

FARKLI TOPRAKLAMA KALIPLARI İÇİN ELEKTRİKSEL GEÇİCİ ÖZELLİKLERİN ARAŞTIRILMASI

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Bir topraklama sisteminin güvenliği, elektrik tesisatlarının çoğunda operasyonel güvenlik için iletim ve dağıtım ağında hayati bir rol oynar. Kaçak akım ve aşırı akım koruma röleleri uygulaması topraklama sistemlerinde en çok tercih edilen yöntemler arasındadır. Bu çalışmada, topraklama sisteminin güvenlik performansını araştırmak için yeni bir topraklama kalıbı önerilmiştir. Metodoloji, doğal ve kimyasal topraklama geliştirme malzemeleri üzerinde yapılan kapsamlı saha deneyleri ile titizlikle kanıtlanmıştır. Farklı nem seviyeleri ve gerilim gerilimleri altında doğal ve kimyasal iyileştirme malzemeleri arasında bir performans karşılaştırması yapılmıştır. Farklı topraklama malzemelerine dikey olarak yerleştirilmiş üç bakır çubuğa 0.85-3.76 kV aralığında çeşitli ayarlanabilir gerilimler uygulanmıştır. Saha deneylerinden elde edilen sonuçlar Ayrık Dalgacık Dönüşümü kullanılarak analiz edilmiştir. Deneyler, doğal topraklama geliştirme malzemelerinin elektrotların etrafında düşük toprak direnci sağladığını, yüksek dirençli toprak için uygun maliyetli bir çözüm olarak hizmet ettiğini ve IEEE 80 güvenlik standartlarına uygun olduğunu göstermektedir.-----

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Anahtar kelimeler: Topraklama güvenliği, DC yüksek gerilim, Doğal topraklama geliştirme malzemesi, Ayrık Dalgacık Dönüşümü (DWT), Topraklama direnci.

SUMMARY

Ph.D. THESIS

INVESTIGATION OF ELECTRICAL TRANSIENT CHARACTERISTICS FOR DIFFERENT GROUNDING SYSTEMS

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The safety of a grounding system plays a vital role in the transmission and distribution network for operational safety in the majority of electrical installations. The application of residual current and overcurrent protection relays is among the most preferred methods in grounding systems. A novel grounding cake is proposed in this study to investigate the safety performance of the grounding system. The methodology is meticulously demonstrated through extensive field experiments on natural and chemical grounding enhancement materials. A performance comparison was carried out between natural and chemical enhancement materials under different humidity levels and voltage stresses. Various adjustable voltages in the range between 0.85-3.76 kV were applied to three copper rods vertically planted into different grounding materials. The results from the field experiments were analysed using Discrete Wavelet Transform. The experiments demonstrate that natural grounding enhancement materials give low ground resistivity around the electrodes, serve as a cost-effective solution for high resistive soil, and are in conformity with the IEEE 80 safety standards.

December 2020, 166 pages.

Keywords: Grounding safety, DC high voltage, natural grounding enhancement material, Discrete Wavelet Transform (DWT), Grounding resistance.

1. INTRODUCTION

The history of the electrical grounding system predates Edison times where Donald W. Zipse & P. E states at the beginning man-made electricity used to use earth, “the surface of the terrestrial ball we live on”, as the return path for continuous electrical current 140 years ago [1]. In 1882, Edison ‘s dc electrical generation is considered the first machine to use a grounding electrode. The machine used two conductors, positive and negative, and neutral return current connected to a gas pipe, which entered the earth. In 1913, to standardize the materials and equipment installation methodology, the first National Bureau of Standards (NBS) was created, and in 1961, Standard 80 was published to protect workmen with the substation by installing the first grounding buried wires against the step and touch potentials. In 1923, a new rule was established to introduce earthing of load frames (resistors) to prevent electric shocks by indirect contact [2]. Later on, in 1955, the rule was applied to industrial 3 phases systems by adding fuses and some electrical conditions to limit the fault current. Thus, until 1970, the grounding system was developed for the lone purpose of limiting fault current.

Since the 1970s, most industrialized countries agreed to put in place some International Standard after understanding fault currents and lightning phenomena [2]. The understanding that Low Voltage (LV), Medium Voltage (MV), and High Voltage (HV) networks and loads are to be earthed for the safety of the equipment but also the people brought up new objectives in the electrification community, such as

- Fixing the potential of conductors with respect to the earth in normal operation
- Limiting the voltage between earth and the equipment in case a fault happens
- Limiting the rise in potential for MV faults
- Put protective devices that avoid the risk of electric shock for people.

The purpose of a grounding system is to create a secure path to dissipate the fault electrical current to protect while continuing to provide power to the connected devices and people.

The enhancing materials targets to improve the electrical properties of the soil around the grounding electrodes. Ground Enhancement Compound (GEC) refers to the standards for conductive materials which can be used to decrease the ground resistance value [3]. After the

soil characteristic was identified to have a considerable effect on ground fault currents in 1981, the demand for a good grounding system increased [4]. Many methods were used throughout time to reduce the earth's resistance. Deep-grounding-well methods, different design of grounding electrodes and the latest is the implementation of conductance enhancement material. The deep-grounding-well method is used for mountains area and is about finding the optimum depth which the best resistance. It is not affected by seasonal and climates changes [5-6]. The other method is to increase the diameter or the length of grounding rods [5]. However, this method has a high material cost and can't be applied in limited space [5-7]. The trend has shifted towards the use of ground enhancement materials or commonly referred to as backfill materials. The utilization of these materials has become essential to achieve a low earth resistance especially in high soil resistivity areas (rocky, sandy, etc.). Many studies have already been conducted on different types of enhancement materials to investigate their properties, characteristics, and behaviors. There are two types of enhancement materials so far natural and chemical materials.

Although many studies were done on different backfilling materials, very few have investigated their behaviors under high impulses conditions. Thus, in this study, a specific grounding rods arrangement is established and the rods are excited with high voltages impulses in order to check the characteristics of bentonite and proposed our proposed natural cake under lightning conditions. Furthermore, a comparison between the performance of Chemical Ground Enhancement Material (CGEM) and proposed Natural Ground Enhancement Materials (NGEM) is also proposed.

2. MATERIALS AND METHODS

2.1 Modeling of Grounding System

Most electrical power stations are built into the earth thus creating direct contact between people and the soil. For this reason, the soil constitutes one of the main parts in most electrical



circuit accidents and the impedance of the soil affects greatly the safety of people. Consider the scenarios Figure (1) below:

Scenario1: High resistive soil (Sand, kaolinite, plastic)

Scenario 2: High conductive soil (metallic, clay, loam)

Scenario 3: Semi-conductive mixt soil (a mixture of Clay & Sand)

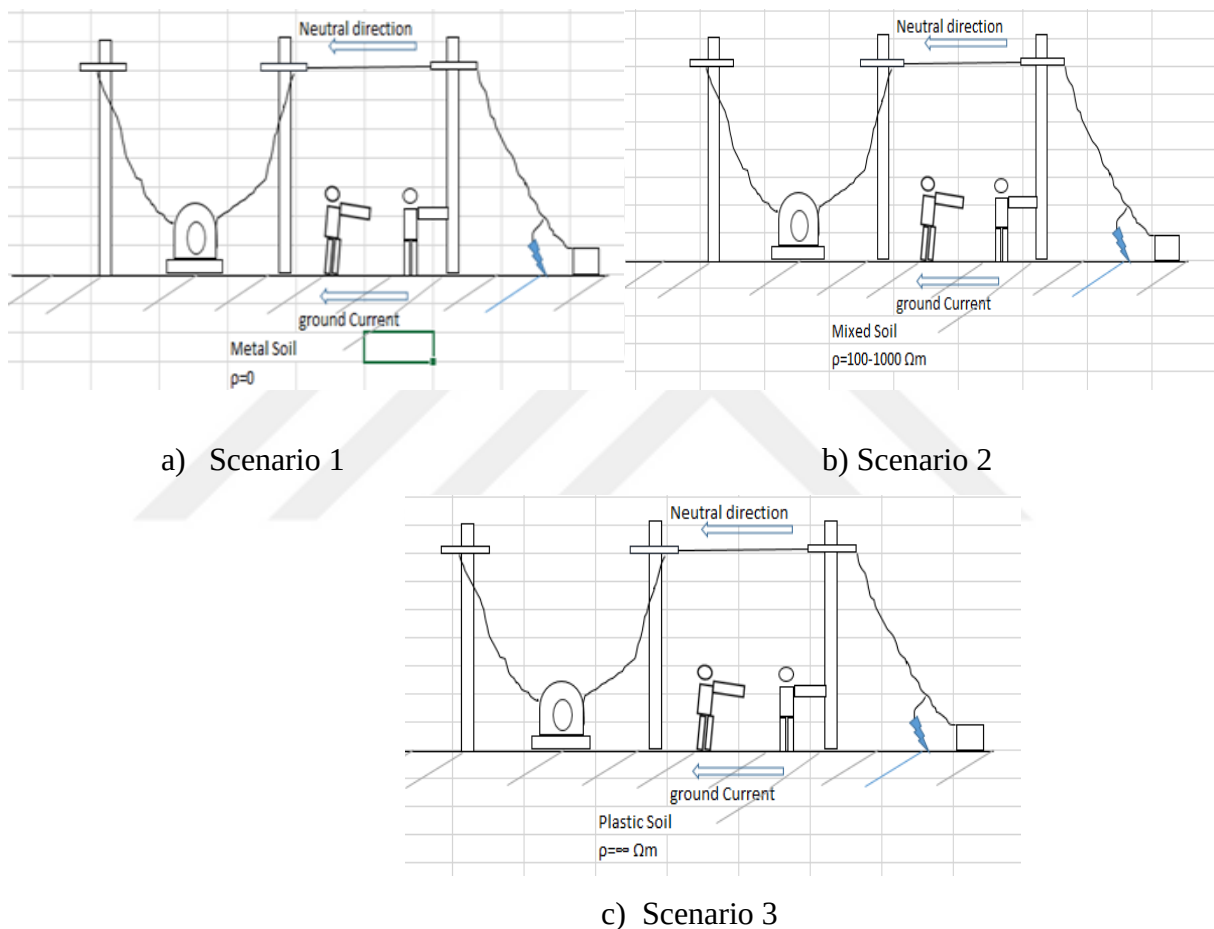


Figure 2.1: 3 types of electrical soil characteristics a) Scenario 1, b)Scenario 2, c) Senario 3

The plastic soil because of the high resistivity will not conduct any current thus the ground current will zero. The metal soil will conduct the fault current through the soil. These 2

conditions are the safest for people and equipment. But the mixed or semiconductive soil is most common in real life.

The grounding method can be classified into two main groups: the conventional methods and the alternatives methods.

2.1.1 Conventional Grounding

2.1.1.1 One Rod Grounding Method or Pipe Grounding Method

It is the simplest grounding type. By inserting a single electrode into the ground, the resistance to the ground depends on the surrounding soil resistivity. Throughout the year's many researchers have come up with different equations to calculate the ground resistance based on one single rod [8,9].

$$R = \frac{\rho}{2\pi C} \quad (2.1)$$

R is the resistance in Ω , ρ is the soil resistivity in $\Omega.m$ and C is the electrostatic capacitance of the single rod in Farad. Electrostatic capacitance formula is given as:

$$C = \frac{13.25 L}{1.55 + \log \frac{L}{d}} \quad (2.2)$$

With L and d the length and d the diameter of the rod respectively.

The ground resistance of the single method could also be computed by rod

$$R = \frac{100\rho}{2\pi L} \times \ln \frac{8L}{d} - 1 \quad (2.3)$$

The particularity of the pipe method is applied on a rod with a diameter of over 13 mm.

The most commonly used method in the grounding system calculation is the Dwight method.

$$R = \frac{\rho}{2\pi L} \times \frac{(\ln 4L) - 1}{r} \quad (2.4)$$

ρ represents the soil resistivity ($\Omega.m$); L is the length of the rod in cm and r is the radius in cm.

2.1.1.2 Multi Grounding System Method

For grounding systems comprised of two or more rods, the electrostatic capacitance Eq. (2.5) can be calculated for each rod in consideration with the separating distance between each following rod and as the summation of the equation (2.1) [8].

$$C = \frac{61L}{3.52 + 2.3 \log\left(\frac{L}{d}\right) + \frac{L}{S} + \frac{1}{3}\left(\frac{L}{S}\right)^2 + \frac{1}{5}\left(\frac{L}{S}\right)^5} \quad (2.5)$$

2.2 Alternative Grounding Method

This group covers mostly the method covered by the IEEE 80-2000 standard. The grounding grid is an intermeshed network of conductors. The most commonly used methods are Sverak Method, Laurent Nieman Method, Schwarz, and the Thapar Gerez methods. A brief explanation of these methods would follow in this section.

2.2.1 Laurent and Niemann Method

The ground resistance depends mainly on the area covered by the substation and also the soil resistivity of the mentioned area. The non-uniformity of the soil resistivity causes resistance to change [10]. By estimating the minimum resistance value at a particular depth h from the surface of the ground, Laurent and Niemann formulated the ground resistance to be:

$$R = \frac{\rho}{4} \sqrt{\frac{\pi}{A} + \frac{\rho}{L}} \quad (2.6)$$

$$L = l + n * h \quad (2.7)$$

Where A is the area of substation m^2 ; l is the conductor length, n the number of rods, L the total length of the buried conductor, and h is the height of the grid from the surface.

2.2.2 Sverak Method

Sverak method is a continuation of the Laurent and Niemann method [10]. The difference is Sverak methodology considers the ground grid burial h effect to be large enough and included it in the equation. Thus, the new rearrangement gives;

$$R = c \left[\frac{1}{L} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + \frac{h\sqrt{20}}{A}} \right) \right] \quad (2.8)$$

Laurent-Niemann and Sverak Equations show that the dependence of the resistance to the resistivity. In fact, the resistance is directly proportional to resistivity and inversely proportional to the length of the buried conductors. Resistance is also inversely proportional to the square root of the area. Thus, an increase in the area of the grounding grid will cause a decrease in the order of square-root to the resistivity. If the cost of an area is large, having a big size GS is more recommendable. However, if it is a residential area where the land is limited and expensive, to reduce the ground resistance multiple grounding conductors should be used in the grid designs. It is also possible to increase the total buried length of conductors which will lead to the desired ground resistance in GS designs. However, due to the cost of the copper such method is not advised.

2.2.3 Schwarz Method

Schwarz developed the following set of equations in order to determine the grounding resistance in uniform soil conditions [10]. Schwarz equations are composed of three equations and one equation for merging the three.

$$R = \frac{R_1 R_2 - R_m^2}{R_1 + R_2 - 2R_m} \quad (2.9)$$

where, R_1 , R_2 , and R_m are determined by three different equations. R_1 is determining the ground resistance of a grid formed by straight horizontal wires and represented in the following equation.

$$R_1 = \frac{\rho}{\pi L} \left[\ln \left(\frac{2L}{a'} \right) + \frac{k_1 L}{\sqrt{A}} - k_2 \right] \quad (2.10)$$

where ρ is the soil resistivity in $\Omega \cdot m$, L is the total length of all connected grid conductors in m, a is the diameter of the conductor in m, a' is $(a \cdot 2h)^{1/2}$ for conductors buried at depth h , or a' is on the earth surface, A is the area covered by conductors in m^2 , k_1 and k_2 are the coefficients found by the following equations according to the value of grid depth (h).

The values of k_1 and k_2 in Eq. (2.10) are given in Table below for different values of the grid depth. In the formulations, x is given as the length to width ratio of the grid.

Table 1: k_1 & k_2 values according to grid depth [10]

H	k_1	k_2
0	$-0.04x + 1.41$	$0.15x + 5.5$
$\frac{1}{\sqrt{10A}}$	$-0.05x + 1.2$	$0.1x + 4.6$
$\frac{1}{\sqrt{6A}}$	$-0.05x + 4.13$	$-0.05x + 4.4$

R_2 and R_m are respectively given by

$$R_2 = \frac{\rho}{2\pi nL} \left[\ln \left(\frac{4L}{b} \right) + \frac{2k_1 L}{\sqrt{A}} \sqrt{n-1}^2 \right] \quad (2.11)$$

$$R_m = \frac{\rho}{\pi L} \left[\ln \left(\frac{2L}{L} \right) + \frac{k_1 L}{\sqrt{A}} + 1 - k_2 \right] \quad (2.12)$$

where L is the length of each rod in m, $2b$ is the diameter of rod in m, R number of rods placed in area A .

The grounding grid resistance by computing k_1 , k_2 , R_1 , R_2 , and R_m in the given order, and putting the calculated values in Eq. (2.9).

2.2.4 Thapar-Gerez Method

Thapar-Gerez method is a complex computer software based on the infinite element analysis to determine the resistance of a grounding system. This method works for a system constructed by straight linear conductors laid in a perpendicular direction. The empirical equation is as follow:

$$R = \rho \left[\frac{1}{L'} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1+h\sqrt{(20/A)}} \right) \right] * 1.52 \left[2 \ln \left(\frac{L\sqrt{(2)}}{A} \right) - 1 \right] \frac{\sqrt{A}}{L} \quad (2.13)$$

Where L' is the peripheral length of the grid.

It should be noted that (2.13) doesn't consider the effect of grounding region shapes. The particularity about the Thapar-Gerez equation is, it doesn't change according to the shape of the grid [11]. The factor $\sqrt{A/l}$ is the constant found based on the fact that ground the resistance

of a conductor in a specific area decreases as the length of the area over which the conductor spreads increase.

2.2.5 Multi Layers System Grounding Method

This technique is used for highly non-uniform soils where one- or two-layers grounding systems are not feasible [12]. The multi-layers model is designed by incorporating several horizontal soil layers. A computer program or graphical method is then used to interpret the results obtained from the 2 layers' model.

2.3 Finite Element Grounding Methods

In recent years, the Finite Element Method (FEM) is used for grounding analysis. This method is more accurate compared to the conventional grounding methods discussed above. FEM consisted of currents flow analysis on the potential grid [11-12]. The resistance of the ground is calculated by dividing the voltage by the computed current. The main concerns about this method are the selection of the size of the model, the earth's distance from the grounding system.

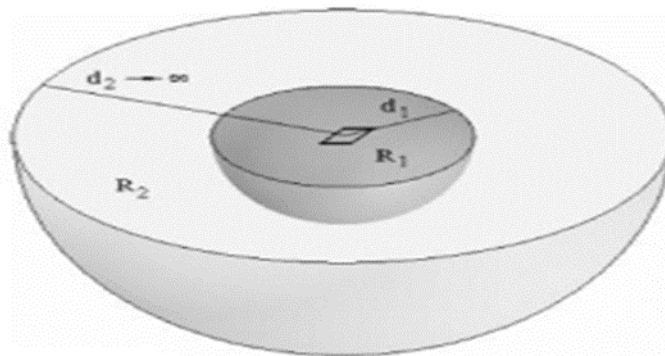


Figure 2.2: Soil model of Finite element [11]

In FEM analysis two main assumptions were considered at the early stage. The first point is, all power frequencies besides 50-60 Hz should be neglected at all stage of the measurement. (Consider the ground resistance doesn't depend on voltage or current in the grid beside the ones recorded between 50-60 Hz). The second assumption is the area should be considered as an infinite flat surface [13].

R_1 , R_2 , d_1 , and d_2 are the variables for the model

d_1 is the distance from the grid to the points where the semi-spherical model of equipotent surface disturbs.

d_2 is the distance from the grid to the points where the electrical potential is zero.

R_1 and R_2 are the resistances inside the semi-spherical surface and outside the semi-spherical surface.

Formulations are simplified as followed:

$$d_1 = \frac{D}{2} + 30 \quad (2.14)$$

D is the diagonal distance of grounding grid.

$$R = R_1 + R_2 \quad (2.15)$$

$$\text{With } R_2 = \frac{\rho}{2\pi d_1} \quad (2.16)$$

To determine R_1 , Eq (2-17) is used

$$R_1 = \frac{V^2}{\text{disssipated power}} \quad (2.17)$$

More simplified equation for R_1

$$R_1 = \frac{(V_g - V_b)^2}{\int_V \frac{E^2}{\rho} DV} \quad (2.18)$$

V_g is the grid potential, V_b is the potential at the point d_1 so the grid resistance is Eq (2.15)

2.4 Definitions

This section contains the basics concepts of electrical grounding systems, the definition of key terms. The later chapter presents detailed design criteria, specific methodologies in greater length, and more detail.

2.4.1 Tolerable Potential Difference at a Location

Safety is the most important factor to consider while designing a grounding system. Step voltage is the surface potential difference to which a human body may be subject to when placed within a meter distance from the ground conductor (through the feet) and any other conducting grounding surface [14]. The tolerable potential or the safe step voltage “E” should not exceed the total ground resistance R and the body current (I_B) as a function of time. When a high

current is conducted through a human body because of an accidental circuit, personal safety is lost. These kinds of accidents are referred to as fault in the power system. “Dangerous current” is any current high enough duration and magnitude to harm a human being. We can calculate that critical value with the following equation [15].

$$E = R * I \quad (2.19)$$

$$R = 6 * c * \rho + 1000\Omega \quad (2.20)$$

$$I = \frac{0,16}{\sqrt{t}} \quad (2.21)$$

I is the tolerable amount of current of the body

0,116 is the Constant of a statistical population of 50 kg, t is the current duration in the second

C is a reduction factor the nominal value of surface layer resistivity,

ρ is Crushed rock resistivity in $\Omega.m$

2.4.2 Step and Touch potential

When a fault current flows through the tower grounding system into the earth, the ground potential in the nearby area rises. The step potential is defined as the difference in potential between a person's foot, considering that the person has been standing in the vicinity of the grounding system when the fault occurred [14]. The touch potential is defined as the potential between an energized object and the feet of a person in contact with the object [15]. Both of these faults are extremely dangerous to people's safety. To avoid such faults, the ground potential rise should be determined, the soil resistivity and the grounding equipment should be limited to the allowance level. Figures 1, are the circuit designs of the step and touch potentials [14].

2.4.3 Ground Potential Rise

Any current passing through resistance will create a voltage (Ohm Law). This law also applies to the grounding system. Thus, in case of fault current (I_g) traveling into the ground of impedance (Z_g), a grading potential namely a voltage is created across the soil the current has passed through [16]. This new voltage is created because of the ground impedance in that area

it is called Ground Potential Rise (GPR). As the voltage propagates into the soil, it becomes smaller and the zero potential is reached by using Equation 2.21.

Ground potential rise or Earth potential rise is defined as the product of the impedance of ground electrodes in the earth and the current flowing through the electrodes [14]. For substations, it is referred to as the maximum electrical voltage a substation grounding grid can reach relatively to a distant point which is considered to be a potential [16]. GPR events are a major concern whenever large electrical current travel into the earth. Whether it is a substation, large transformer, pole, or high voltage tower, grounding safety is required to ensure people and equipment safety [16]. GPR drops considerably around the area of the grounding system, but it is never reaching the zero potential.

$$V_{GPR} = \frac{Z_g \cdot I_g}{2\pi \cdot D} \quad (2.22)$$

V_{GPR} is the earth potential in Volt

I_g is the current flowing into the soil in Ampere

Z_g is the soil resistivity in ohm.meter

D is the distance in meter

2.4.4 Ground Fault Current

A ground fault (I_g) could be generally seen as any contact between ground or an equipment frame and energized conductor as given in figure 3. Any conductive low impedance path

designed to transport the current underground fault conditions from a point to the grounding grid is called the ground-fault current path. [14].

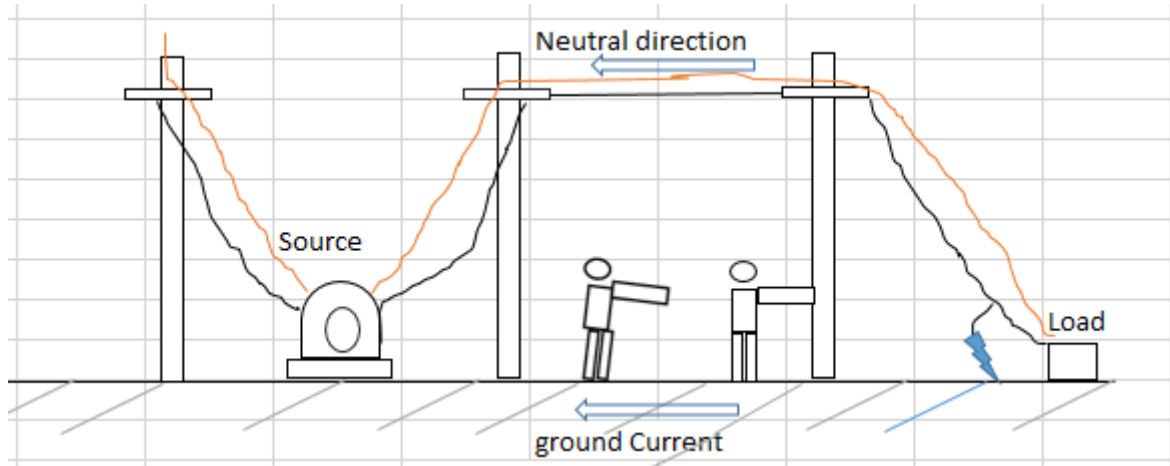


Figure 2.3: Typical fault on Power system

Figure 3 above depicts a single-phase or line to ground fault. When the fault happens, the fault current (I_f) is split into 2 portions. The first part will flow back to the source through the neutral conductor. The other portion will travel back to the source through the ground (I_g). IEEE standard 80 defines the portion that goes to the ground as the current division factor or just split factor (S_f) [17]. The ground current is formulated as followed:

$$I_g = I_f * S_f \quad (2.23)$$

I_f = Total Fault Current

S_f = Split factor

2.4.5 Soil Resistivity

Soil resistivity (ρ) changes from place to place depending on the earth's electrolyte contents (moisture, temperature, minerals, and dissolved salt). For example, soil resistivity is extremely

high in the desert because of the lack of moisture and salt content. Table 1 below gives a general explanation of the different electrical soil characteristics [15].

Table 2: Typical soil characteristics of various terrains [18] (Average over large distance)

TYPE OF TERRAIN	RESISTIVITY ($\Omega.m$)	PERMITIVITY(S.m)
Freshwater lakes, unpolluted	1000	80
Agricultural plains	30	20
Pastoral, low hills	80	15
Flat, marshy	130	13
Pastoral, heavy clay	270	12
Pastoral, Medium clay	250	12
Rocky Soil	500	10
Rocky, sandy	500	8
Low rise city suburbs	1000	6
High rise city centers, industrials areas	3000	4
Sand deserts, arid,	>20000	3

Measuring the resistivity (ρ) of terrain depends also on the depth of measurement electrodes. The formula is as follows:

$$\rho = (E \cdot A) / (I \cdot L) \quad (2.24)$$

E: Applied voltage (V)

A: Cross-sectional area (m^2)

I: Current (A)

L: Length of the sample.

2.4.6 Ground Impedance

The Ground Impedance (Z_g) depends on soil structure, size, and ground electrodes geometry. In short, it is the equivalent impedance seeing by the ground-fault current when flowing into

the earth [14-17]. Ground impedance is a complex value but it is mostly referred to as resistance to the most recent IEEE standard 80 because most of the reactance value for the stations is small and can be ignored. That is why in our case, the reaction is considered to be zero. But, when the size of the electrical ground grid is increased (wind farm, solar plant), the ratio between reaction and resistance has to be considered. Thus, it is an important factor to consider when establishing personal safety.

2.5 Ground Enhancement Material

Ground enhancement materials also called ground enhancement compounds or backfilling materials are conductive materials that are used to improve the conductivity of the ground. It is most effective in rocky and sandy soils where the moisture level is really low. It drastically reduces the earth's impedance thus reducing the size of the grounding system where conventional methods are unsatisfactory. They are maintenance-free, they don't require the presence of water to maintain their conductivity, and also, they don't need any periodical changing.

2.5.1 Natural Ground Enhancement Material

As its name indicates, natural ground enhancement materials (NGEM) are compounds made from biodegradable waste or plant materials. The components are chosen based on their hygroscopic ability and the properties of the soil don't change (ph. level, fertility, and mineral content).

Throughout history, many scientists have tried to find the most suitable materials capable of reducing the grounding resistance efficiently. Eduful et al investigated the properties of Palm Kernel Oil Cake (PKOC) as backfilling material [19]. The study showed that PKOC is largely composed of conductive carbons, and can also absorb moisture about 2.5 times its weights. Furthermore, J.Jasni et al demonstrated that PKOC is an excellent grounding resistance reducer and it maintains the resistance for a long time [20]. Other studies on coconut coir peat, planting clay soil, paddy dust, etc. were also done [21-24]. From all these studies, planting clay soil was proven to be the most effective grounding filler.

Bentonite is a natural clay used as a backfilling material. Research on bentonite started in the 1980s with Warrant R. Jones who introduced it as GEM in Grounding System (GS) [24].

Due to its hygroscopic property, bentonite can retain water up to 5 times its weight and bloats 13 times its dry volume [4]. Kutter. H et al concluded that bentonite improves the GS whole performance by reducing the grounding resistance [25]. Many more scientists looked into the behaviors of the bentonites including Z.R Radakovic et al who studied it under fault conditions [26]. The findings revealed that bentonite doesn't crack under high fault conditions and its thermal stress increases the grounding impedance for a short time. S. Lim and al investigated the behaviors of different enhancement materials under the dry condition and found out bentonite has the lowest breakdown voltage [27]. Bentonite was also studied by V. P. Androvitsaneas et al under-lightning condition, where the performance of bentonite was compared to one the concrete [22]. This study showed that bentonite performance depends on the humidity level of its surrounding area. Their findings demonstrated that bentonite can significantly reduce the grounding impedance up to 80%. The biggest majority of the studies show that bentonite performance depends highly on the weather (temperature, humidity, rainfall, and even the type of soil). However, its biggest disadvantage lays in its high cost and also the fact that it can't found everywhere. Most countries need to import it.

Table 3: List of most used Natural GEM.

Natural GEM	Chemical GEM	Waste GEM	Additive
Paddy dust [4]	Conductive Bentonite clay [27]	iron oxide [4]	Engine oil [34]
coconut peat [4]	MgSO ₄ [15]	Fly Ash [60]	Aluminum powder[34]
Palm oil decanter cake [19][4]	FGGG (graphite-cooper composited grounding material) [35]	Resistance Reduction Additive (RRA) [4]	iron powder
Kenaf powder/fiber [61]	Bentonite [22]	Wood ash [43]	
Palm oil shell [19]	CuSO ₄ [15]	Tyre Ash	metal pieces
Powdered cacao shell [4]	NaCl [34]	palm oil waste [34]	
Concrete [22, 58, 59]	Gypsum [11]	Engine Oil [34]	
Zeolite, Perlite and Vermiculite [36]	Marconite [11]	Coal ashes [34,35]	
LRM [63]	CaCl ₂ [15]	Plaster Waste [35]	

Waste products used as Enhancement Material

Industrial wastes are one of the main sources of pollution. It harms the environment and constitutes a threat to all living beings. For that reason, researchers have started to study the possibility of using them as ground enhancement materials. In recent years, several industrial

wastes have been selected for the ability to reduce the ground impedance. C Gomesa et al used the waste metal compound rich in iron oxide (Fe_2O_3) as backfilling material [28]. The performance of the compound equals that of the conventional enhancement materials. The disadvantage of iron oxide is caused by rust on conventional grounding rods.

The performance of fly ash was examined as enhancement materials by Sin-Der et al. They showed that the application of fly ash reduces 35% after soil stabilization [29]. The mining industry residue called Resistance Reduction Additive (RRA) has also been used to reduce ground impedance.

The investigation of RRA showed a reduced rate of 34% without any water addition and also doesn't corrode grounding rods [30].

2.5.2 Chemical Ground Enhancement Materials

Chemical Ground Enhancement Materials are the most commercially widespread. They can easily be found almost anywhere. They are made from hydrous aluminum silicate, hydraulic cement, carbon, crystalline quartz, sulfur, oil, and chemical additive. Due to their conductivity ability, they are most used in the grounding systems. In the past, grounding systems were designed to reach a particular ground impedance, but nowadays many standards also consider

a certain potential rise value for a grounding system. In Table 4, a comparison for NGEM, CGEM, and Industrial Waste GEM is given below:

Table 4: Comparison between Enhancement Materials

Materials	Advantages	Disadvantages
NGEM	Keep the soil original Ph level	Influenced by rain
	Keep the soil original mineral content	Influenced by temperature
	Keep the soil original fertility level	Influenced by moisture
	Low cost	Influenced by the soil characteristics
	Easy to make	May need yearly maintenance
	Local material	
CGEM	Doesn't require periodical changes	Change the soil original Ph level
	Quick reduction (As soon as it dries)	Change the soil original mineral content
	Durable	Change the soil original fertility level
	Easy to install	Expensive
	Compact design	Difficult to obtain around the globe
	Maintenance free	Filgurite formation on bentonite leads to increase in resistivity
	Hold moisture for a long time	
Industrial Wastes GEM	Recycle Industrial Wastes	Rust of grunding rod
	Less pollutant in the environment	Not much data equired about their effects on the ground.

2.6 Basic Electrical Grounding Theory

2.6.1 Soil as Conductor with Finite Resistivity

In the grounding system soil is considered as any conductor whose resistance increases with its length and decreases as its cross-section area increases [14].

$$R = \frac{\rho * L}{A} \quad (2.25)$$

A large area has a lower resistance. When a fault current is divided between a short wire and a section of the soil, the majority of current will tend to flow in the wire as it has a lower resistance than the soil. However, if the same fault is split between a long wire and a section of the soil, the fault current could flow either way depending on the resistance of the long wire and the characteristics of the soil. If we consider the soil as a large surface, then the current will

mostly travel in the soil as its resistance is inversely proportional to its length and the resistance of the wire will keep increasing.

2.6.2 Electrical Soil and Modeling

The electrical characteristics of the soil depend greatly on the temperature, its moisture content, granular size, salinity level, structure, etc. The good soil data and an excellent soil model are vital if you want to predict where the fault current will travel. Goree defines the electrical soil model as the overall collective group of layers and their respective resistivities which compose a particular soil [14]. The safety of any site or electrical installation depends greatly on the soil structure as it determines the way the fault current will behave. Data about the soil can be used to predict whether the fault currents are more likely to flow on the surface of the soil, or a deeper layer and to calculate the optimal burial depth for the ground rod to achieve an effective safety current channeling. IEEE Std 80. provides reliable calculation to determine the safe thresholds based on the soil characteristics data [31].

2.6.3 Different Soil Treatment Methods

Soil resistivity is the characteristic of the main materials that constitute the grounding resistance [31-33]. Soil resistivity changes from 10 $\Omega\cdot\text{m}$ to over 10000 $\Omega\cdot\text{m}$ in an electrical

substation. All methods that mean to decrease the soil resistivity in a region is called Soil Treatment in an electrical substation.

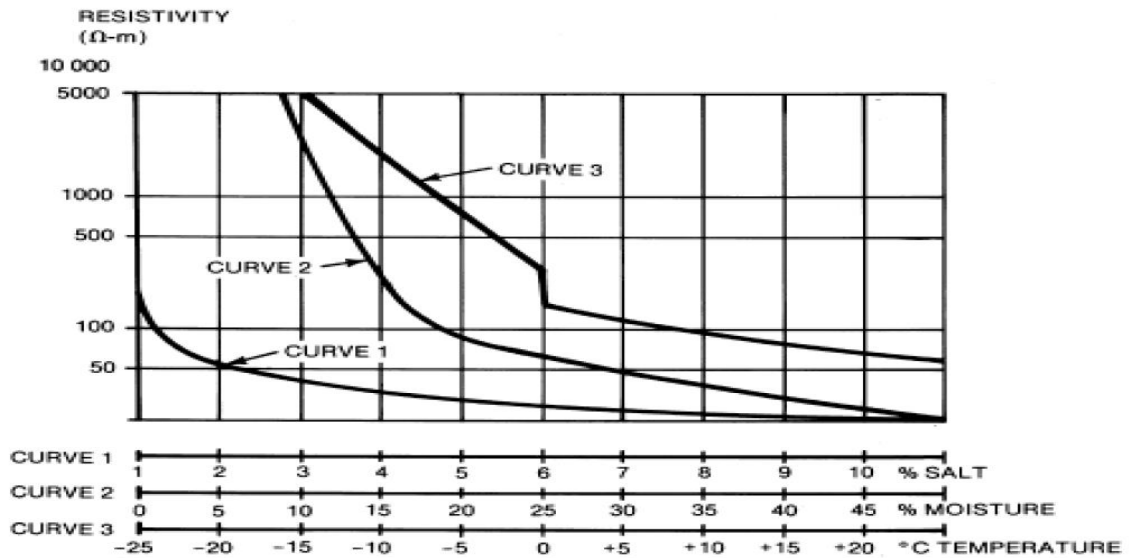


Figure 2.4: Effect of chemical content, moisture, and temperature on soil resistivity [31]

IEEE std 80 shows the soil resistivity varies mostly with the temperature, the chemical content, and moisture level [31]. In figure 4 when the moisture level is below 20%, the soil resistivity rises. The temperature impacts the soil resistivity mostly in extreme cases. For instance, if the temperature is around the freezing level and the soil resistivity increases greatly. Finally, the chemical content affects the resistivity mostly because of the salt or other chemical good ionizers.

2.6.4 Soil treatment: Addition of Electrolytes

The soil resistivity might be high for an area where the soil is pure [32]. Meaning the majority of layers in that area is dominated by one substance. This kind phenomenon happens when there are no electrolytic materials in the soil, thus it becomes a poor conductor. For such cases, a range of soluble substances (Sodium chloride, Sodium carbonate, magnesium sulfate) can be added to the soil. Clark and Watkins investigated and showed the disadvantage of the

use of salt as Ground Enhancement Compound (GEC), because of its corrosive effect and salt dissolved issues by natural drainage [34].

2.6.5 Soil Treatment: Improvement of Moisture Retention

In an extremely dry area such as desert, or sandy and mountain areas, a drop of the moisture content provokes an exponential increase in the soil resistivity. Thus, adding backfilling materials around the conductors prevents excessive loss of moisture thus keep the soil resistivity at an acceptable range [35,36]. The GEM or backfilling materials are used for this purpose. Nowadays, the most used is bentonite and conductive concrete.

Others soil treatment methods worth mentioning

- Improvement of surface contact of grounding rods. (used in stony area)
- Deep driven Rods
- Explosion methods
- Parallel Grid method

2.7 The lightning Surge in the Transmission Line

2.7.1 Surge Arrester

The surge arrester is used to protect the equipment against transient faults entering the system. It provides a low impedance path to the ground for the transient voltage which exceeds the threshold voltage [37]. The most used surge arrester in high voltage installation is the Metal Oxide surge Arrester (MOA) or Zinc Oxide Arrester which was invented by Meidensha in 1960 [38]. The over-voltage protection mechanism can be divided into segments to obtain the correct representation of the nonlinear voltage to current relation around the threshold voltage. The description is in the equation (2.26) and the representation of an MOA typical V-I characteristics is shown in the Figure below.

$$I_{aar} = \begin{cases} K_{seg} \frac{U^\alpha}{U_{aar}} & \text{if } a < u < b \\ K_{seg} \frac{U^\alpha}{U_{aar}} & \text{if } b < u < c \end{cases} \quad (2.26)$$

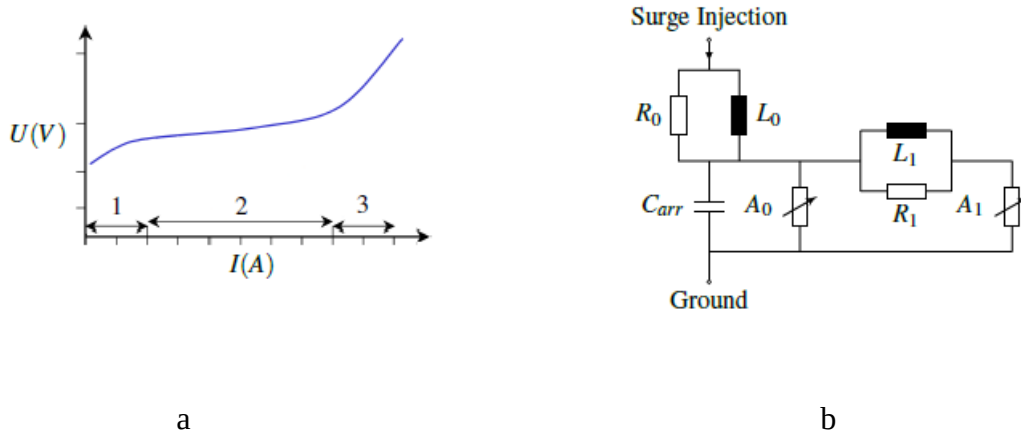


Figure 2.5: a) Representation of MOA typical V-I characteristics b) The circuit diagram of a typical MOA [39,40]

U_{aar} is the reference operating voltage of surge arrester, K_{seg} is voltage segment factor, α is surge arrester exponential factor, I_{aar} is the current created during the suppression of voltage.

Figure 2.5 is represented on a logarithmic scale and is divided into 3 parts. The first represents the normal operating range and the current loss, the second one shows the breakdown characteristics region and the last one is the full breakdown region.

2.7.2 Soil Property and Power Current Injection and Measurement

The performance of power frequency conditions is usually measured by the grounding system resistance. The grounding resistance can be defined as the ratio of potential rise and the impressed current as stated in equation (2.27).

$$R = \frac{U}{I} \quad (2.27)$$

The electrical characteristics of the soil interact with the buried grounding structure when a fault current is injected (directly flowing or flowing by dispersion into the soil). Thus to evaluate

the performance of a GS for any given soil resistivity ρ and grounding device configuration k , the following equation can be used [41].

$$R = k\rho_{soil} \quad (2.28)$$

Many factors influencing the electrical properties of the soil are its chemical composition, porosity the size of the grain in addition to temperature, and the moisture content. So far there exist many methods to analyze the soil properties such as:

- Laboratory sampling gives a deep and detailed analysis of the soil sample's electrical and chemical characteristics. Due to the high cost of geological drilling, the method is not much preferred [42-45].
- Another method called Electrical Resistivity Tomography (ERT) was developed to compensate for the gap in the previous method. The ERT consists of injecting current into the soil with the help of current electrodes and the electric potential drop is read by using two other electrodes. Depending on the site, many electrodes array configurations can be used to determine the lateral and vertical values of soil resistivity. Vertical Electrical Sounding (VES) is all part of the ERT. This technique is used to map geologic variations such as fractures zones, areas of high salinity, lithography of the soil, to detect the presence of groundwater, a saturated area even the contamination level of a certain area. It results in a 1D image of the soil for the VES, a 2D image for the profile, and a 3D image for the volume of the analyzed area [42,46,47].
- Wenner method principle is another Sounding measurement technique. As shown in the Figure2.6, this technique requires four equidistant rods placed in a straight line. The outer loop represents the current and the inner is the voltage/potential loop [48]. A generator

injects a current into the soil through the electrodes with the recorded voltage, the resistance is calculated with Kirchhoff's voltage law

$$R = \frac{V}{I} \quad (2.29)$$

The resistivity ρ is obtained by using the equation (2.30)

$$\rho = 2\pi a R \quad (2.30)$$

The resistivity is calculated at the depth of $4\pi a$. It must be taken into account that $a \geq 4\text{m}$ and the depth of the electrodes should be less than $\frac{1}{20a}$ [49].

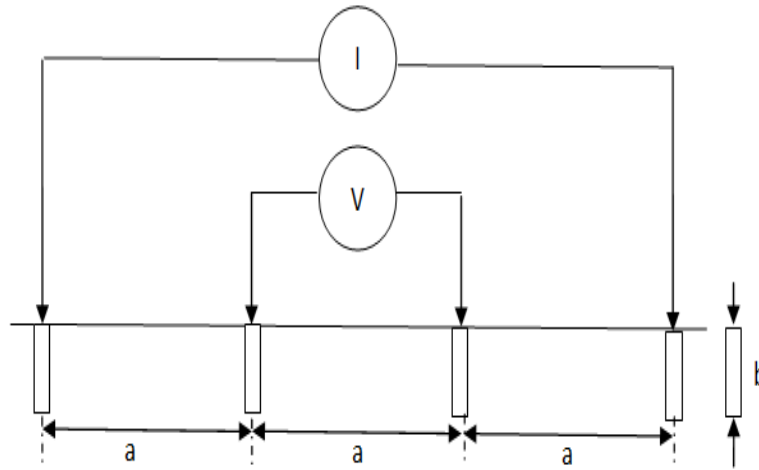


Figure 2.6: Wenner's four-pin four-point method diagram [48]

The last electrical sounding measurement technique is the Schlumberger Method. The Schlumberger method is also based on the same measurement principle as the Wenner method.

The only difference is the positioning of the electrodes [50-51]. After obtaining the resistance from equation (2.29), the resistivity is calculated with:

$$\rho = \frac{\pi \left(d^2 - \frac{a^2}{4} \right) R}{4} \quad (2.31)$$

d is the distance between the current electrodes and a is the distance between potential electrodes.

This method is time saving especially if multiple measurements need to be carried out on the field. Contrary to the Wenner methods where all 4 electrodes have to be replaced for each measurement, in the Schlumberger method only the outer layers need to move to obtain measurement at different depth.

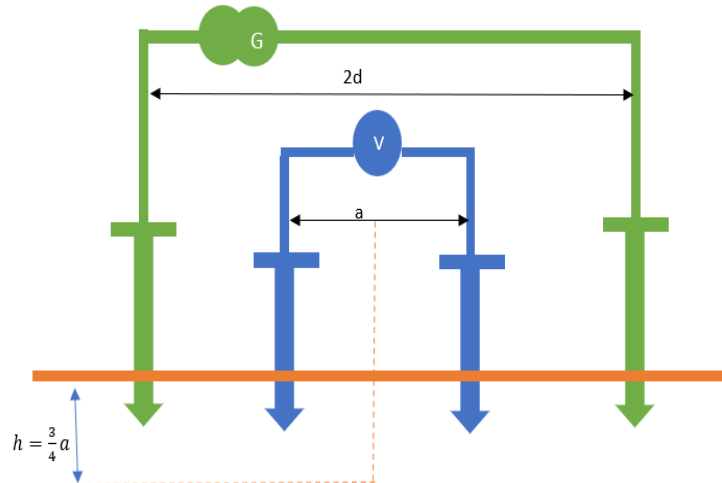


Figure 2.7: Schlumberger measurement principles [52]

Table 5: Classification of soil resistivity [53]

Class	Range
Low	$\rho_{\text{soil}} < 100 \, \Omega\text{m}$
Medium	$100 \leq \rho_{\text{soil}} < 300 \, \Omega\text{m}$
High	$300 \leq \rho_{\text{soil}} < 3000 \, \Omega\text{m}$
Very High	$\rho_{\text{soil}} \geq 3000 \, \Omega\text{m}$

2.7.3 Diagrams of Grounding Grid

The grounding grid equivalent circuits in this section are based on the transmission line model. The most fundamentals are as followed:

a) Single Horizontal Ground Wire

Considering the fundamental of the transmission line model, a part of the grounding mesh can be represented using the circuit element shown below. The figure represents a grounding conductor of length l , a radius r . The resistance and the inductance are represented in per-unit length while conductance and expressed according to the nature of the surrounding soil. Contrary to features of the transmission cables where the insulation losses are kept to a minimum, grounding cables are designed to have the maximum current dispersion into the soil [47]. A grounding wire consists of internal and external impedance. The internal resistance r is

calculated by equation (2.32) and depends on material resistivity ρ_{cond} , the cross-sectional area of the wire a , and the length of the wire l .

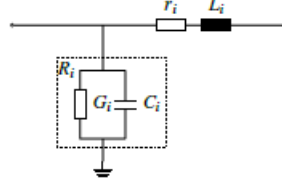


Figure 2.8: Grounding grid equivalent circuit [40]

$$r_i = r_j = \frac{\rho_{cond}}{\pi a^2} \quad (2.32)$$

For a short conductor with a large cross-sectional area, the inductance and the internal resistance are so small that they can be negligible in the high impulse conductions [60-62]. Thus, only the external inductance is considered and is found by

$$L_i = L_j = \frac{\mu_0}{2\pi} \left(\ln \frac{2l}{a} - 1 \right) \quad (2.33)$$

From the soil property, the shunt conductance and the capacitance are found by

$$G_i = G_j = \frac{\pi}{\rho_{soil} \left[\ln \left(\frac{2l}{\sqrt{2}ad} - 1 \right) \right]} \quad (2.34)$$

$$C_i = C_j = G_i \rho_{soil} (\epsilon_0 * \epsilon_{r_{soil}}) \quad (2.35)$$

b) Mutual Effects between Horizontal Ground Wires

Mutual effects between grounding wires happen when lightning surges excited grounding wires in GS. The existence of mutual effects on any 2 or more exciting segments depends on

the distance between the conductors, and the characteristics of the soil [54]. The diagram of the mutual effects between horizontal ground conductors is below:

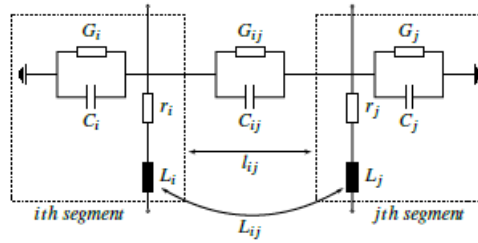


Figure 2.9: Diagram of mutual effects between buried horizontal ground conductors

2.8 Materials

In this thesis, a new grounding cake is proposed. This study aims to investigate the characteristics of differences and the soil reduction performance between bentonite and our new cake. For this purpose, in our new cake, fresh palm oil fruit (in Figure 2.10) and coconut peat (in Figure 2.11) are used as resistance reductive additive. As shown in Figure 2.12, a sack of 20 kg of commercial bentonite is used as CGEM. To increase the conductivity of our new cake, Aluminum and iron powder were added. The percentage of each material is given in Table 4



Figure 2.10: Fresh Palm oil fruit



Figure 2.11: Coconut peat



Figure 2.12: 20 kg Sac of Bentonite

Table 6: List of elements in proposed natural enhancement material

No	Natural Enhancement Material	Percentage (%)
1	Fresh Palm Oil waste	53.81
2	Coco Peat	13.57
3	Iron powder	1.87
4	Aluminum powder	1.87
5	Cement	16.59
6	Soil & Sand	12.29

For simplicity, the following acronyms are used:

ZB= The transient impedance of bentonite.

ZN = The transient impedance of proposed natural enhancement material.

ZE = The transient impedance of normal soil.

H= Humidity level.

NA= Not Available.

cur NG= Natural enhancement material current.

cur Ben= Bentonite current.

2.9 Experimental Methodology

This study was conducted on an open field with the use of (0.85-3.76) kV high voltage impulse. The experiment also showed that natural enhancement material performance can exceed the performance of bentonite depending on the humidity level in the ground and the voltage stress. For data collection, each rod was given an impulse voltage every 0.72 ms for 4.8 s. The Cockcroft voltage generator was used to generate impulses (Figure 2.13). This circuit can generate voltage impulses up to 30 kV. The circuit was composed of a parallel connection of 7 capacitors of 3 μ F and 8 high voltage diodes. The input of the generator was connected to a transformer with a turn ratio at 230V- 1kV. Two resistors were connected to the circuit, at the tail 10 k Ω and the front 40 Ω to limit short circuit current and get a good wave shape. The voltage level was measured by Fluke 80K-40 high voltage probe with a ratio 1000:1 and with

a measurement time of 4.8 s. All the equipment was calibrated according to IEC 60 and they were tested for safety [57]. A Fluke 190-504 digital scope meter oscilloscope was used to read the voltage and the current signals and MATLAB software was used for experimental data acquisition and analysis.

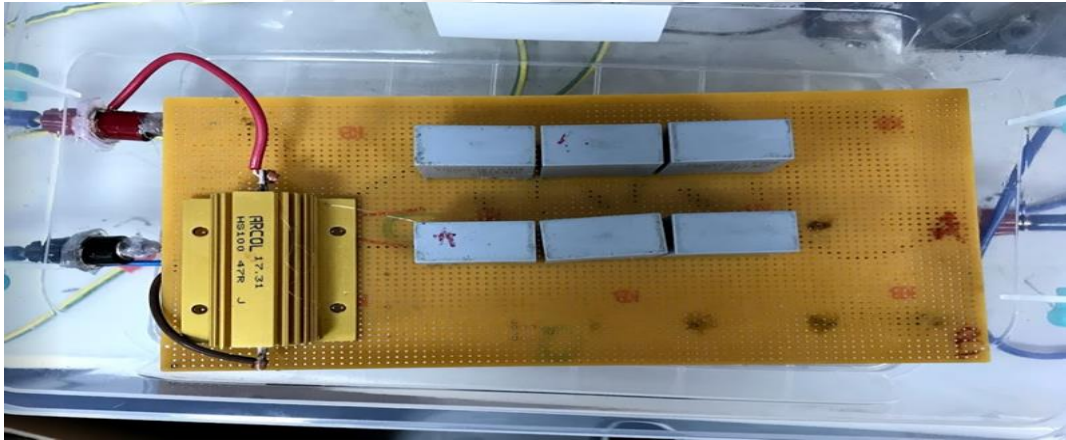
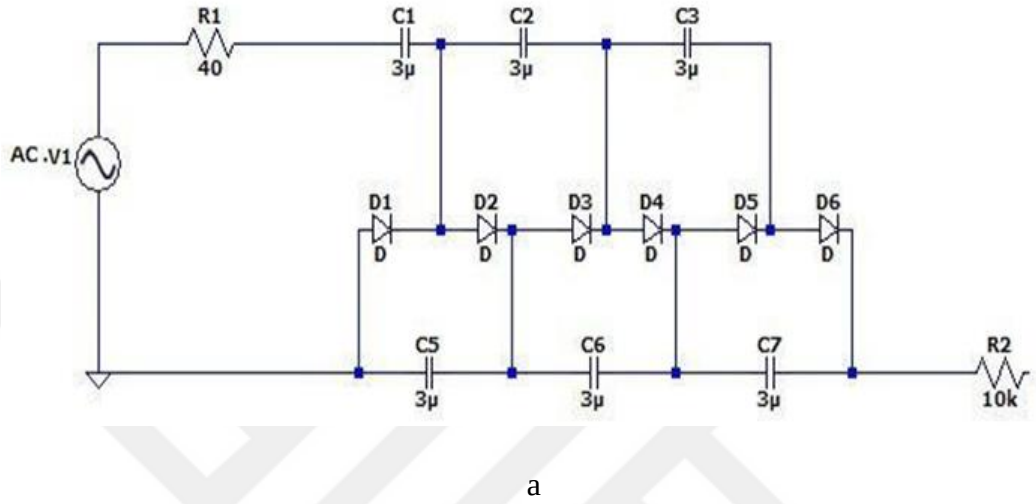


Figure 2.13: Cockcroft generator a) Circuit Diagram b) Photograph

The experiments were conducted on a vacant field inside Istanbul University-Cerrahpasa Campus, Avcilar, Istanbul, Turkey. The measurement of soil resistivity lasted for 10 months. Three grounding rods of 0,8 m each namely Rod1, Rod2, Rod3 were injected with different impulse voltage stresses respectively as Rod1-Rod3 and Rod2-Rod3. Rod1 (Figure 2.14.a) was

driven into commercial slurry bentonite, Rod2 (Figure 2.14.b) was placed into a mashup of natural grounding enhancement materials, Rod3 (Figure 2.14.c) was planted into natural soil.

The soil impedance at the test field changes through seasons may go up to 800 Ω/m depending on the season and its corrosive nature.



a

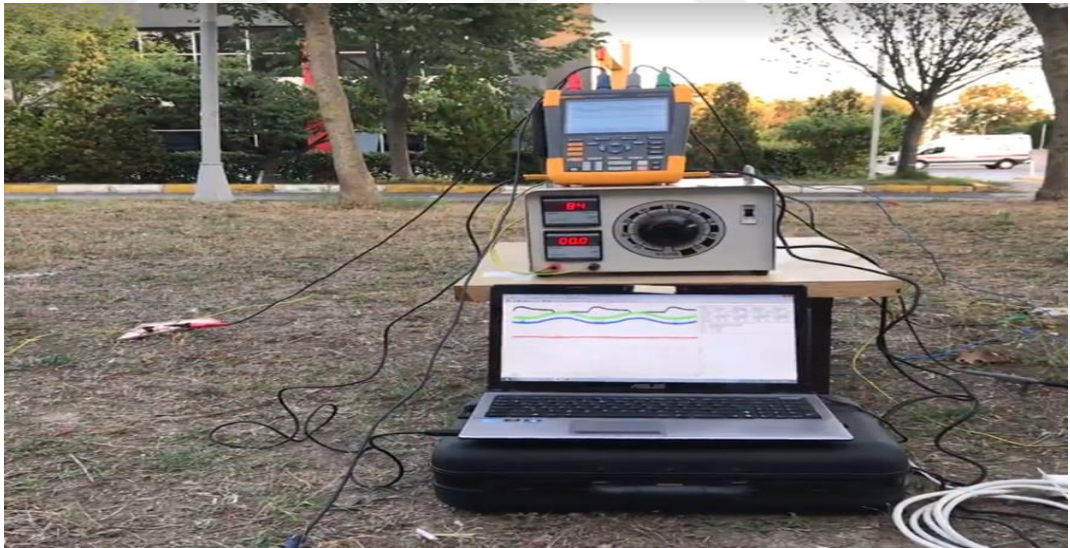


b



c

Figure 2.14: Grounding rod encased in a) slurry of bentonite b) slurry natural ground enhancement material c) normal soil



a

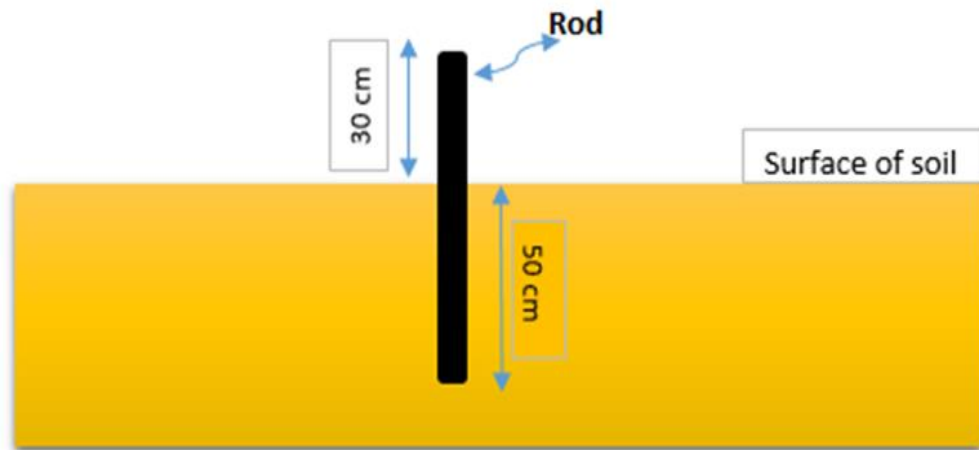


b

Figure 2.15: Photo of measurement equipment a) Front view b) Panoramic view

In figure 15, the front view and panoramic view of the measurement equipment are given respectively as a and b.

Besides, all the rods were placed in cylindrical pits of 0.5 m at an equidistance. The pits were filled with enhancement materials. The 4 poles measurement method with Megger DET2/3 auto earth tester was used to measure the soil resistivity and the humidity was measured with CEM DT-8820 environment meter [48]. The soil resistivity was measured every time there was an experiment from February to November 2019. A complete lay of the experiment can be seen in Figure 2.16.



a



b

Figure 2.16: The layout of the testing grounding rods a) single rod b) Photo of single rod-hole

Figure 2.16.a shows a schematic of the way the electrodes were planted and how much GEM was used to fill the 0.5 m hole. Figure 2.16.b shows the planted electrode before the use of backfilling material.

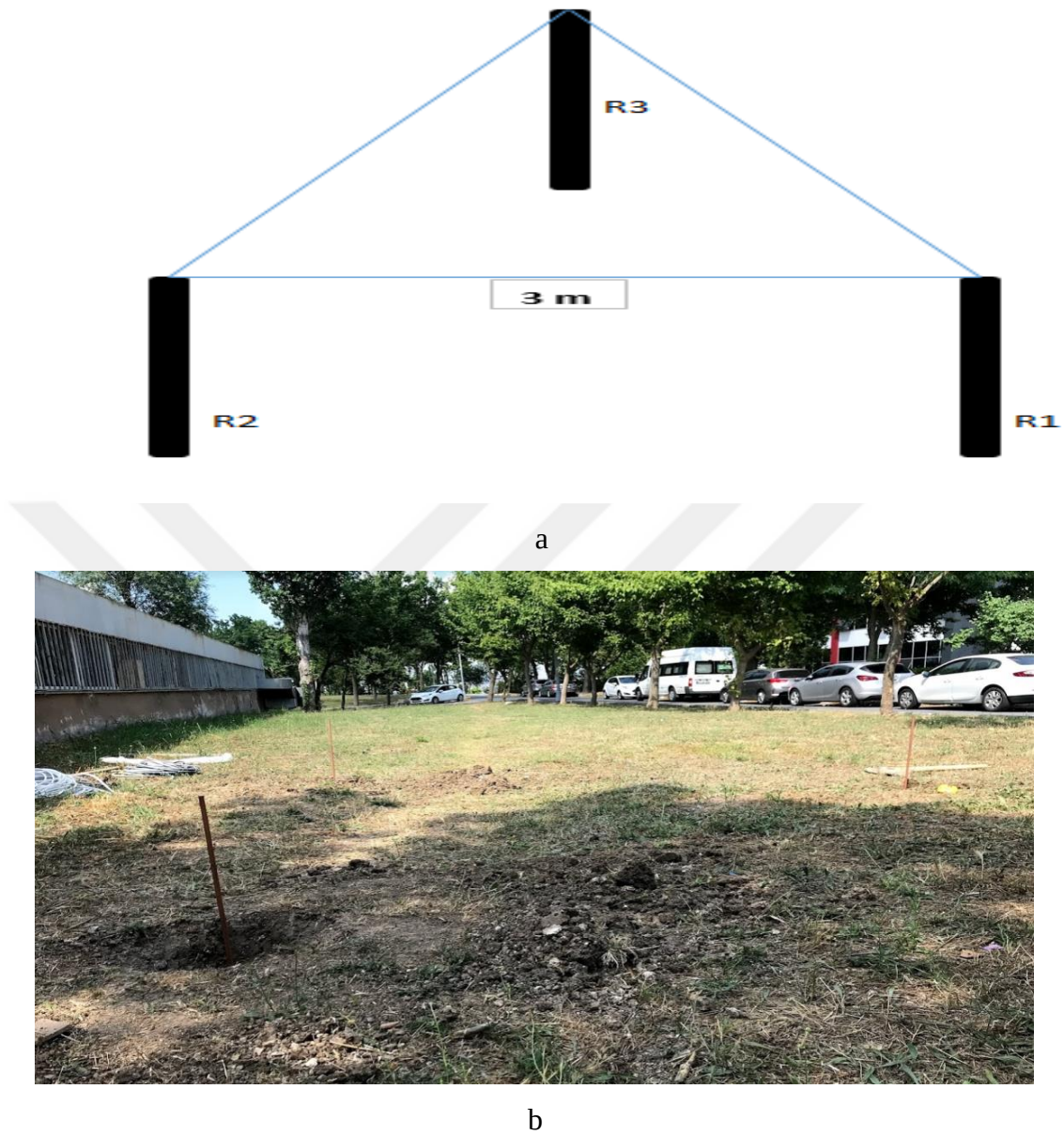


Figure 2.17: The layout of the testing grounding rods a) 3 rods diagram b) Photo of Rod positions

Figure 2.17 shows the complete layout of the experiment. In Figure 2.17.a, the positions of the rods are given and in Figure 2.17.b, the real photo of the rods is depicted.

3. RESULTS

To understand the behaviors of our GEM in transient conditions, we apply high impulse voltage at the tip of all grounding electrodes. Transient impedance was assessed in 7 different voltages and 5 different humidity levels were investigated. In some cases, excessively high stress has occurred on the measuring equipment. This caused very high currents to pass over the measuring probes. Measurement could not be made due to exceeding the tolerance limit value of measuring equipment. This situation is expressed in the text with Not Available (NA).

To calculate the percentage of transient impedance for each enhancement material with respect to ZE, equation (1) and equation (2) are used. K1% is the change of transient impedance of bentonite with respect to transient impedance of normal soil; K2% represents the change of transient impedance of natural enhancement material with respect to transient impedance of normal soil.

$$K1\% = \frac{Z_B}{Z_E} * 100 \quad (3.1)$$

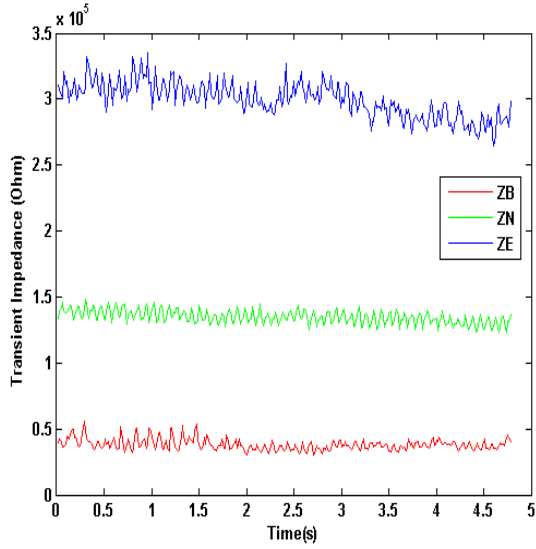
$$K2\% = \frac{Z_N}{Z_E} * 100 \quad (3.2)$$

It should be noted that the lower the percentage is the higher the reduction rate of soil impedance. For each table, the changes were calculated by using the formulas above for each voltage and humidity level.

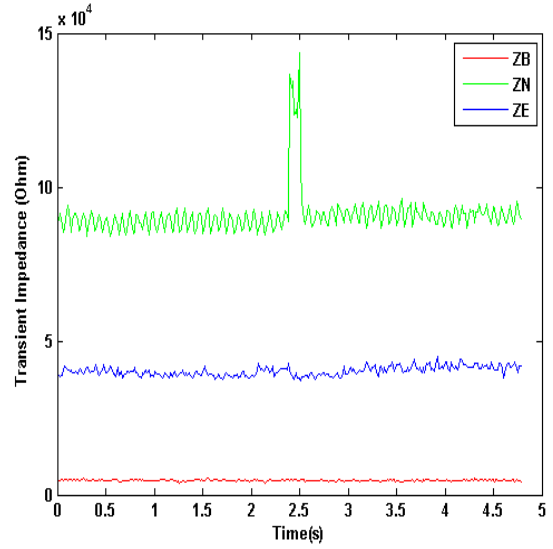
This section is divided into two. The first section is about the analysis of the simulation results, the calculation, and the comparison of the soil impedance reduction rate for the bentonite, NGEM, and the normal soil. The second section is about the analysis of dissipated current. To have a better understanding of the phenomenon happening inside each material during the transient condition, the currents are analyzed with Discrete Wavelet Transform (DWT).

3.1 Transient Impedance Calculation and Comparison

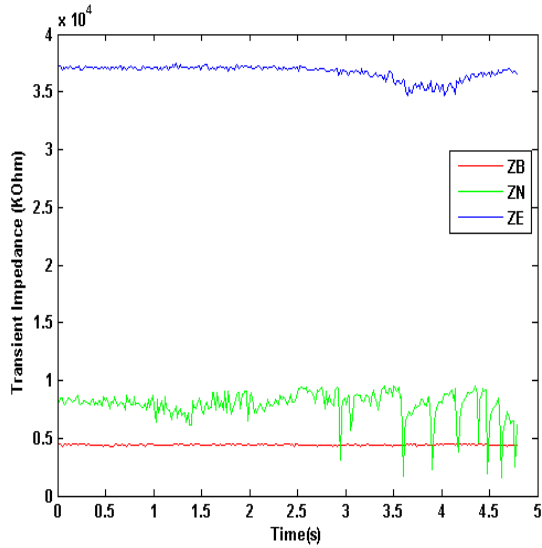
In this section, the change in transient impedance according to different humidities was calculated and given below.



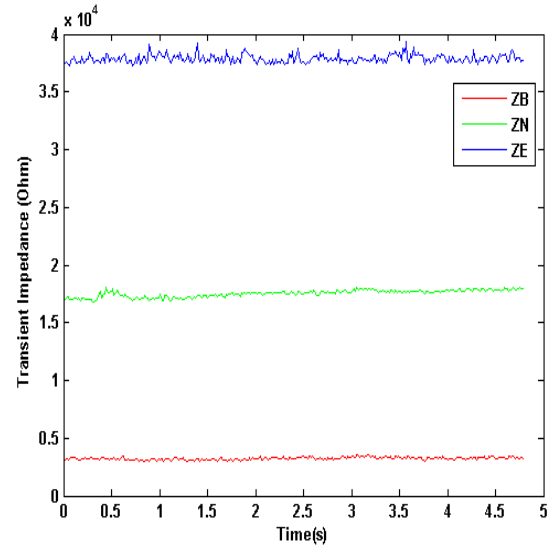
a



b



c



d

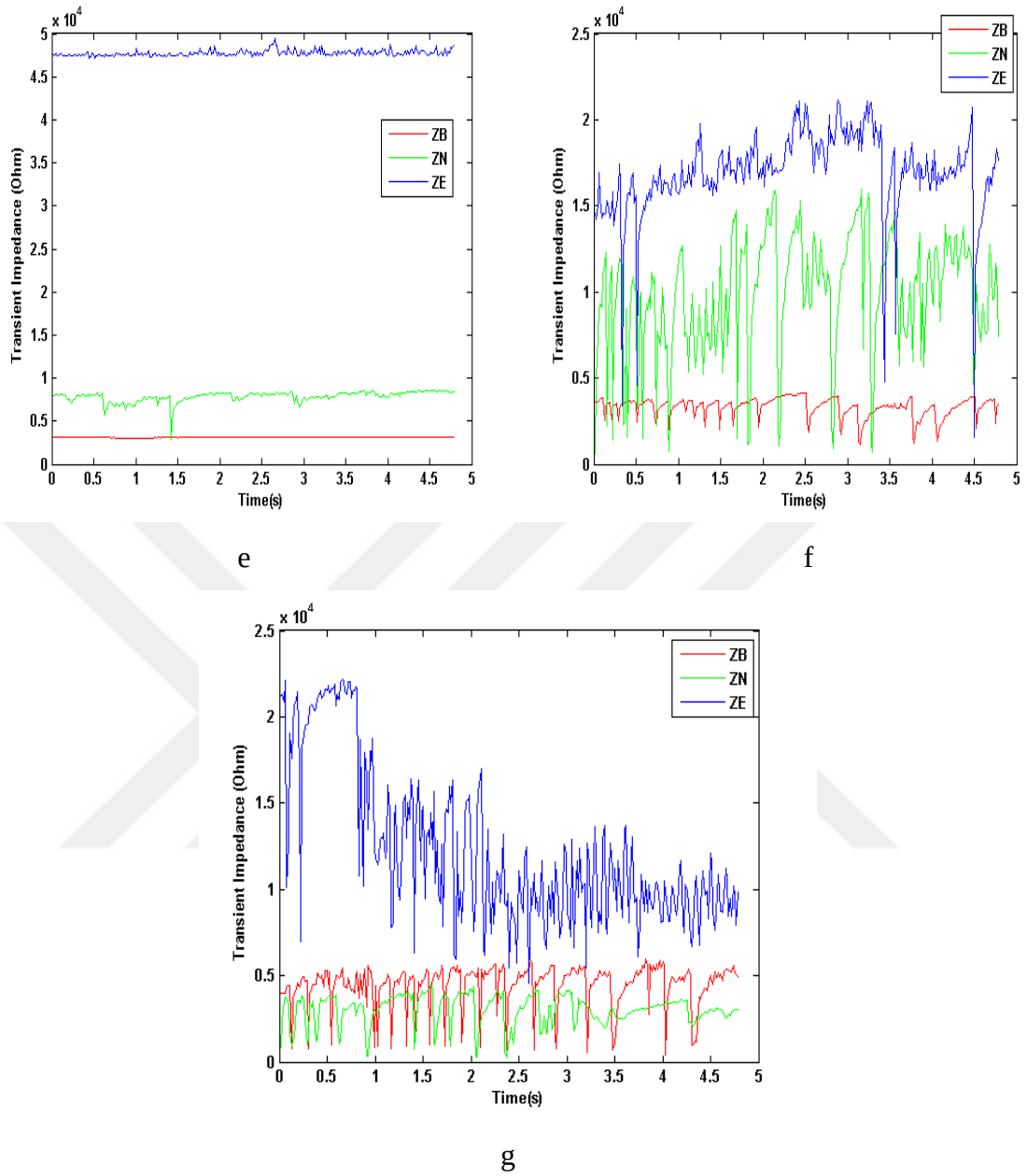


Figure 3.1: Transient impedance for 3 different rods at H= 68% a=856 V b=1054 V c=1465 V d=2050 V e=2670 V f=2900 V g=3760 V

Figure 3.1. a show the transient impedance is the highest with over 300 k Ω . At H= 68%, the bentonite's reduction rate is about 13% (K1) and 46,66% (K2) for the natural ground enhancement material.

In Figure 3.1.b, at V=1054V a drop in the transient impedance is recorded compared to V=854V. The behaviors of the ZB and ZE are somehow uniform; the ZN on the other hand shows a peak at 2.5 s. This brusque rise of impedance may be because of the changes in the

current magnitude flowing into the soil. The bentonite performs better than NG with a 25% reduction rate.

In Figure 3.1.c for $V=1465V$ for the bentonite, the resistivity of the soil around the electrode dropped to 9% in reference in ZE, compared to 47% for NG.

Figure 3.1.d shows a real improvement in the performance of NG. The reduction for NG went from 47% for $V=1465V$ to 19% for $V=2050V$. Thus, more than 28% better results. The bentonite registers a higher reduction of 8%.

At 2670V, a reduction of 13% for bentonite and 21% for the natural GEM is shown in Figure 3.1.e.

In Figure 3.1.f, excessively high stress has occurred on the measuring equipment. This caused very high currents to pass over the measuring probes. Measurement could not be made due to exceeding the tolerance limit value of measuring equipment. This situation is expressed in the text with Not Available (NA).

In Figure 3.1.g the average values for ZB, ZN, and ZE were considered for the calculations in this case. Refer to Table 7-a. At 3670 V, both materials recorded about the same reduction rate of 15%.

Table 7: a) Impedance for all voltages at $H=68\%$

a) The percentage of the impedance of reduction with ZE as a reference at $H=68\%$.

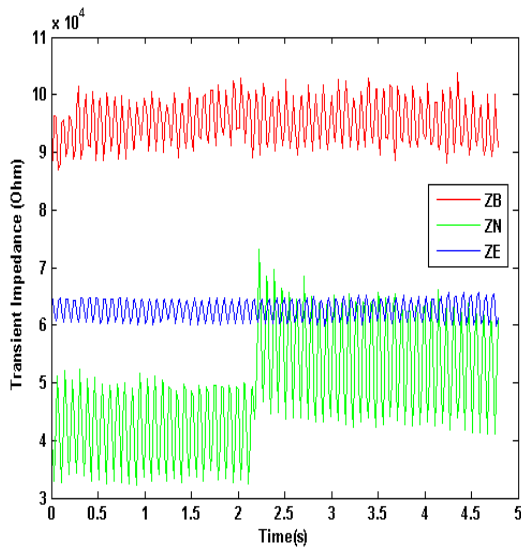
Voltage (V)	ZB (k Ω)	ZN(k Ω)	ZE(k Ω)
854	40	140	300
1054	NA	NA	NA
1465	9	8	40
2050	4	17	40
2670	3	8	37
2900	3	9	37
3760	3	7	20

a

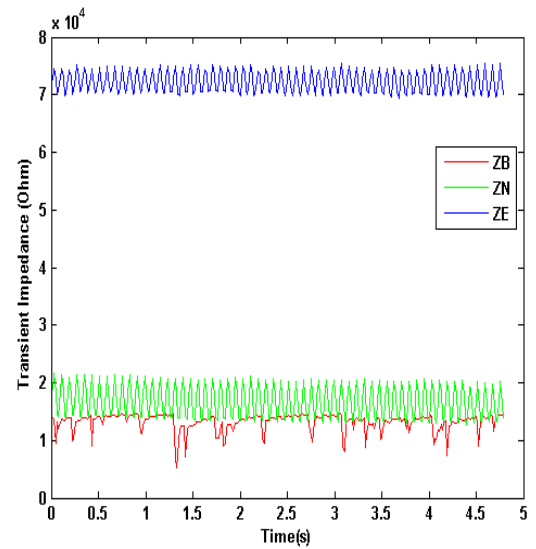
Volt (V)	854	1054	1465	2050	2670	2900	3760	AVG
K1%	13.33%	NA	22.50%	10.00%	6.38%	8.11%	15.00%	12.50%
K2%	46.67%	NA	20.00%	42.50%	17.02%	24.32%	35.00%	31.00%

b

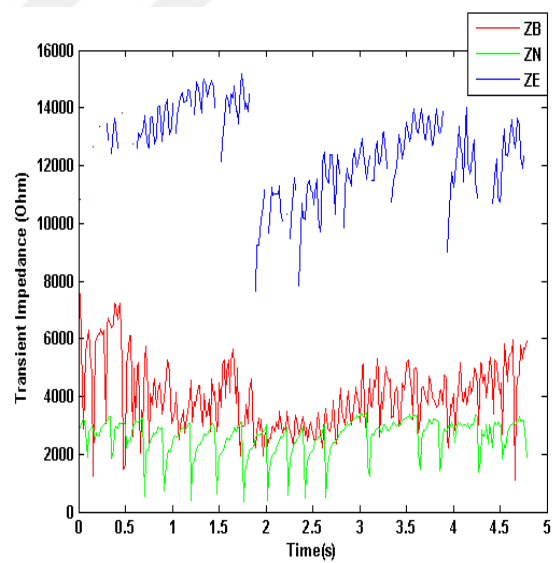
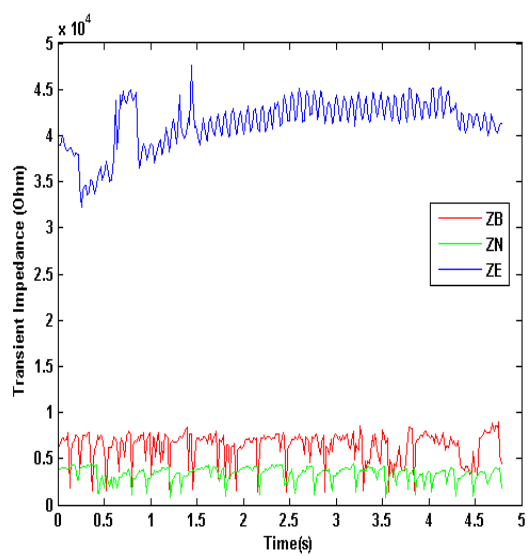
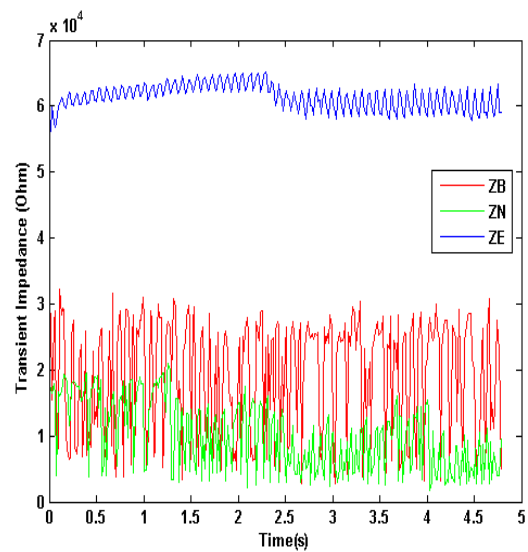
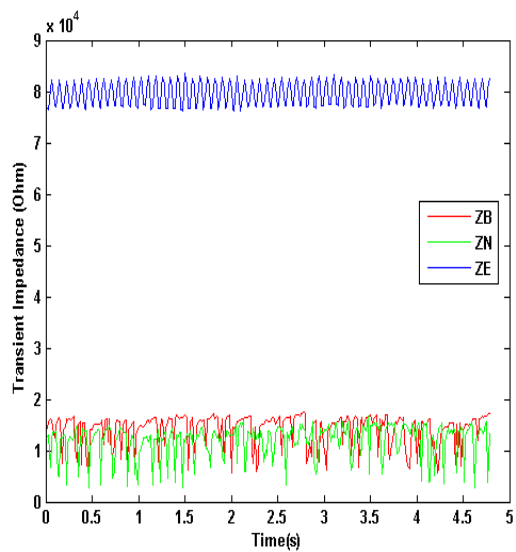
Considering Table 7-a, ZB and ZN behave more linearly than ZE. The value of the transient impedances for both materials decreases as the voltage increases. Table 7-b reveals the bentonite has the highest average reduction rate with 12.5% (K1%) versus 31% (K2%) for proposed natural enhancement material. Based on the average K1% and K2% (Table2-b), different safety levels are required for bentonite and natural enhancement at a 68% humidity level.



a

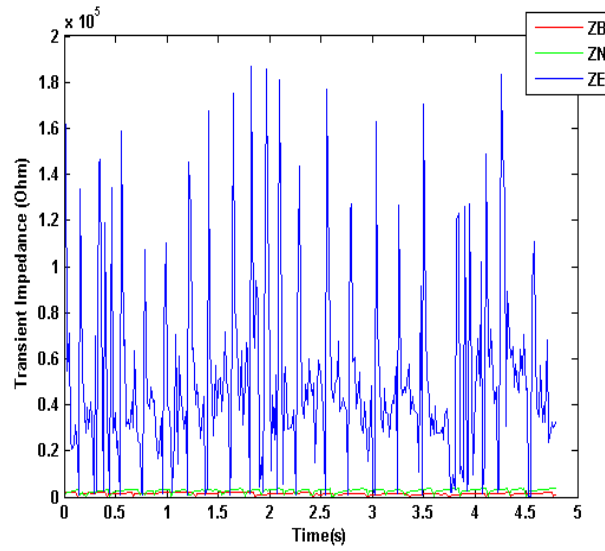


b



e

f



g

Figure 3.2: Transient impedance for 3 different rods at H= 70% a=856 V b=1054 V c=1465 V d=2050 V e=2670 V f=2900 V g=3760 V

In Figure 3.2.a, bentonite transient impedance reaches 90 K Ω , exceeding the transient impedance of the normal soil and the natural enhancement material. The soil impedance reduction rates are 6% and 141% for the normal enhancement and the bentonite respectively. The performance of natural enhancement is much better.

The graphs in Figure 3.2.b show small variations in the transient impedances. ZN at V=1054V has dropped 43.75% compared to ZN at V=854V. ZB has also decreased drastically from 90 k Ω to 15 k Ω at V=1054V. We can also notice some linear aspects of ZN, ZB, and ZE. The soil transient impedance has decreased by 20% and 23.33% for bentonite and the natural enhancement respectively

In Figure 3.2.c, similar behaviors can be seen in Figure 26 a and b. ZN and ZB are very close values 13 k Ω and 18 k Ω respectively. 18.57% and 25.71% were registered for K1 and K2. Natural enhancement has better performance.

In Figure 3.2.d the average value for ZN and ZB was considered in this case as the graphs oscillate a lot. ZN was calculated to be 12 k Ω and ZB was 16 k Ω . The natural enhancement shows a better result of 20% compared to 27% for the bentonite.

In Figure 3.2.e, ZN has the smallest transient impedance with 4 k Ω and ZB recorded a 6 k Ω . The reduction rate in reference to ZE is 13.33% and 8.88% for the bentonite and the natural enhancement respectively. Natural enhancement has better performance

In Figure 3.2.f due to the sensitivity of the measurement equipment, some data could not record. Thus, this case falls into the Not Available NA cases.

Figure 3.2.g because of the sensitivity of the measurement equipment, some data could not record. Thus, this case falls into the Not Available NA cases

Table 8: a) Impedance for all voltages at H= 70%

b) The percentage of the impedance of reduction with ZE as a reference at H= 70%.

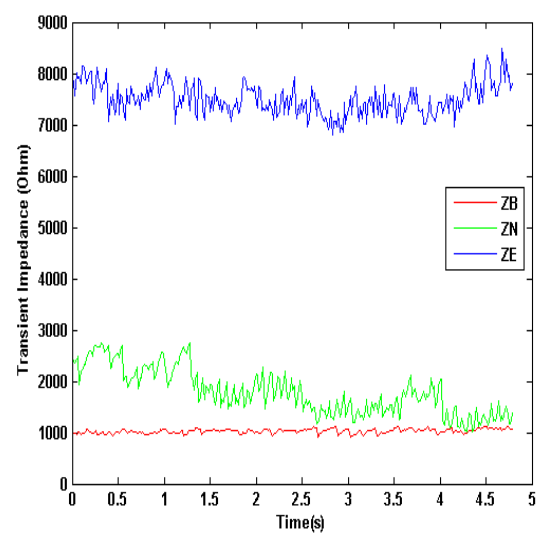
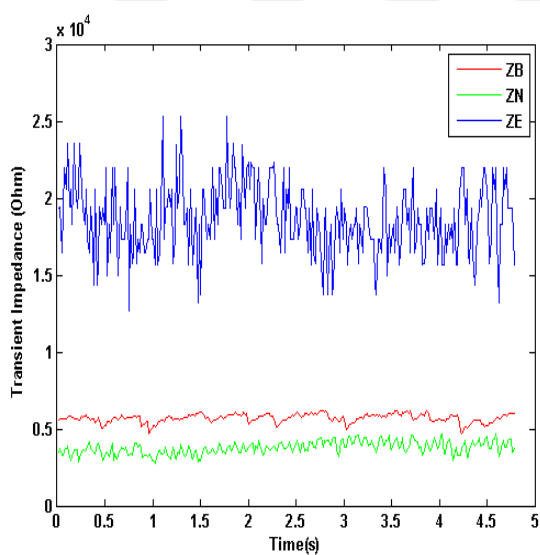
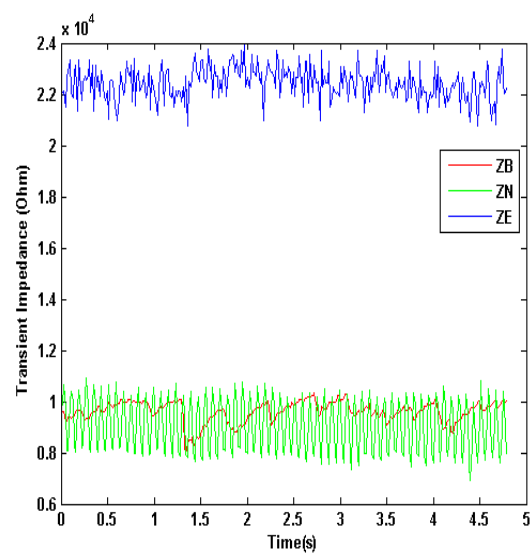
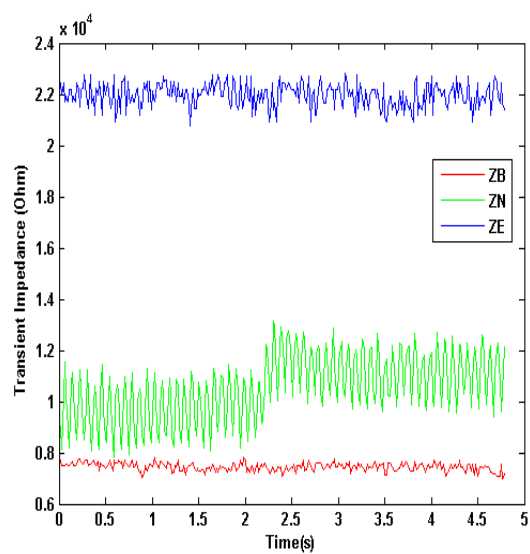
Volt(V)	ZB(k Ω)	ZN(k Ω)	ZE(k Ω)
854	90	40	62
1054	15	17.5	75
1465	13	18	70
2050	16	12	80
2670	6	4	45
2900	NA	NA	NA
3760	NA	NA	NA

a

Volt (V)	854	1054	1465	2050	2670	2900	3760	AVG
K1 %	145.16%	20.00%	18.57%	20.00%	13.33%	NA	NA	43.41%
K2 %	64.52%	23.33%	25.71%	15.00%	8.89%	NA	NA	27.49%

b

At a 70% humidity level, some improvements are noticed in natural enhancement material. Compared to H=68% the bentonite reduction rate has worsened by more than 30.91% and the natural enhancement reduction rate has improved by 3.51%. The natural enhancement material performs better with an average of 15% (Table 8-a, b). Considering Table7-b for both materials, it can be said that their safety levels are different at a 70% humidity level. Table 8-a shows an increase in voltage causes a decrease in transient impedance.



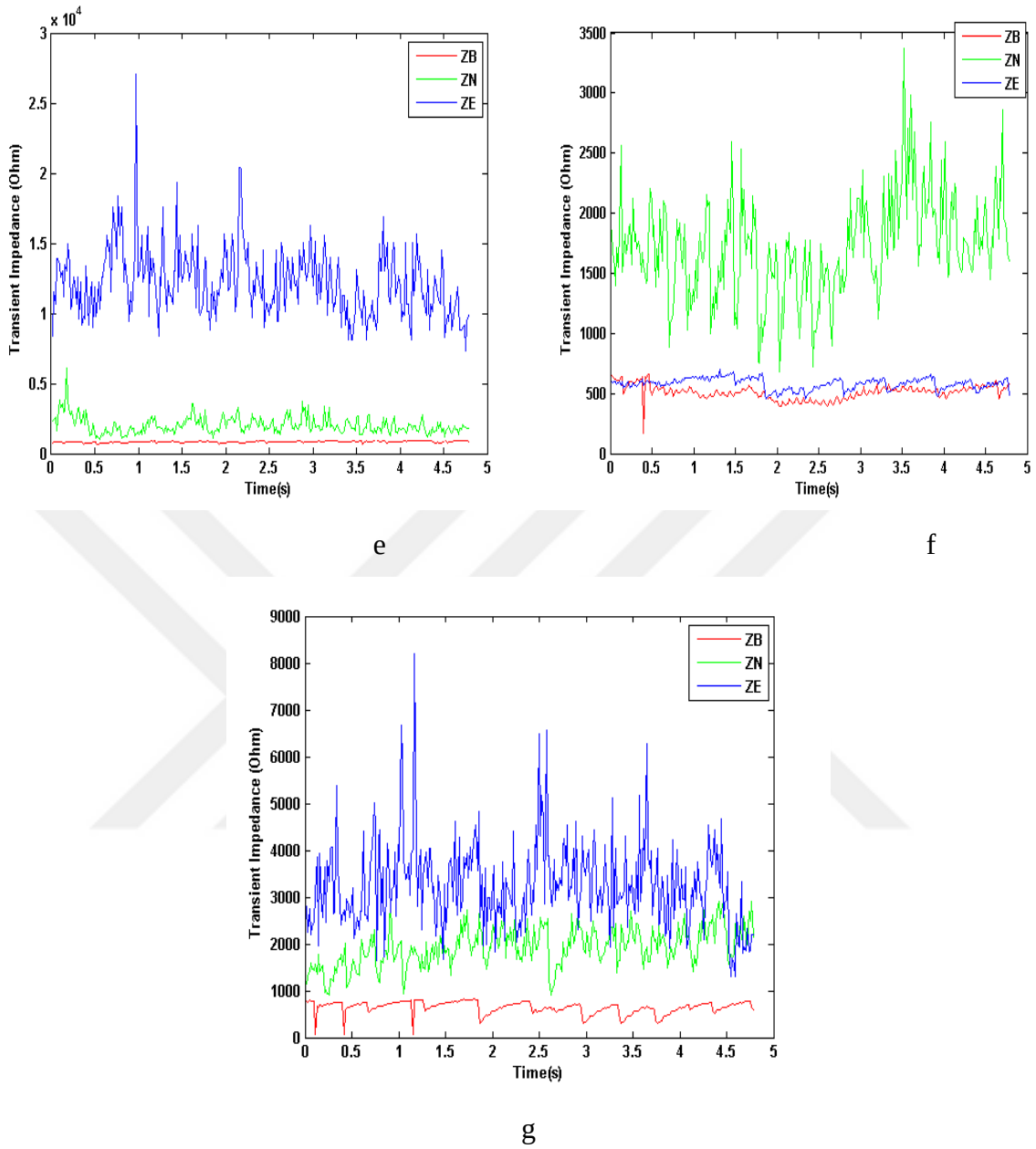


Figure 3.3: Transient impedance for 3 different rods at H= 72% a=856 V b=1054 V c=1465 V d=2050 V e=2670 V f=2900 V g=3760 V

From Figure 3.3.a, the transient impedances (ZN, ZB, and ZE) at H=72% are much smaller compared to the previous humidity levels. The bentonite registers a transient impedance of $7.6\text{K}\Omega$ at H=72% versus $70\text{K}\Omega$ and $40\text{K}\Omega$ at H=70% and H=62% respectively. At this voltage and humidity, 35% and 55% reduction rates are recorded for the bentonite and the natural enhancement material.

In Figure 3.3.b, the average values for ZN and ZB were considered. ZB and ZN registered similar soil reduction rates in reference to ZE. $K1 = K2 = 39\%$. A comparison between K1 and K2 values, from Figures 21 a and 21 b, shows the bentonite reduction capacity was reduced by 4% and natural enhancement reduction capacity has improved by 16%. Although the ZN and ZB values have decreased, the $K1 = 34.55\%$ at $V=854V$ and $K1 = 39.13\%$ at $V=1054V$. Thus, an increase in voltages doesn't necessarily mean a higher reduction rate.

In Figure 3.3.c, ZN, and ZB are more linear than in the two previous figures. ZN has the lowest transient impedance of $4K\Omega$ for $K2=20\%$ of the soil impedance reduction rate. ZE registers $5.5K\Omega$ for $K1=27.50\%$ of soil impedance reduction rate. The performance of the natural enhancement material is higher than the bentonite at $V=1465V$ & $H=72\%$.

Figure 3.3.d shows a major reduction of $4.5 k\Omega$ in ZN value compared to the previous voltage. K1 and K2 values are 12% and 25%. This case shows the highest reduction rates for both bentonite and natural enhancement.

Figure 3.3.e ZN and ZB remain the same. But their percentage of reduction has increased to 10% and 20% for the bentonite and the natural enhancement material respectively.

Figure 3.3.f due to the sensitivity of the measurement equipment, some data could not record. Thus, this case falls into the Not Available (NA) cases.

In Figure 3.3.g shows low values for ZN, ZB, and ZE due to the high humidity and voltage level. 30% and 40% percentage of reduction were registered for bentonite and the natural enhancement material respectively.

Table 9: a) Impedance for all voltages at H=72%

b) The percentage of the impedance of reduction with respect to the ZE at H= 72%.

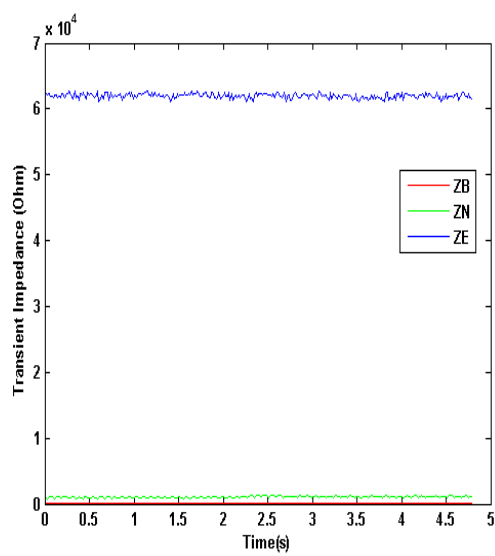
Volt(V)	ZB(k Ω)	ZN(k Ω)	ZE(k Ω)
854	7.6	12	22
1054	9	9	23
1465	5.5	4	20
2050	1	2	8
2670	1	2	10
2900	NA	NA	NA
3760	0.9	1.2	3

a

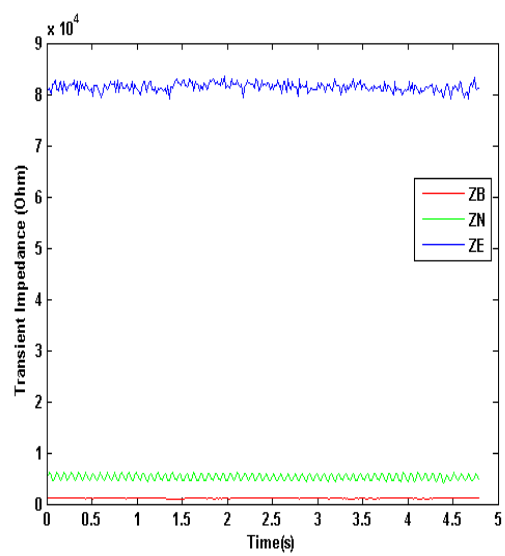
Volt (V)	854	1054	1465	2050	2670	2900	3760	AVG
K1 %	34.55%	39.13%	27.50%	12.50%	10.00%	NA	30.00%	25.61%
K2 %	54.55%	39.13%	20.00%	25.00%	20.00%	NA	40.00%	33.11%

b

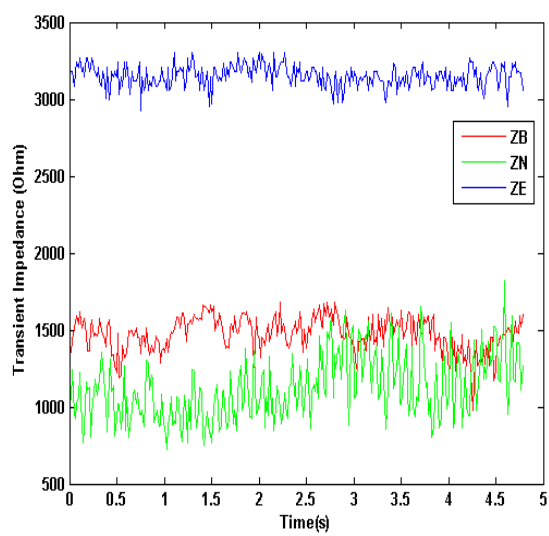
Comparison among Tables 7,8,9-a shows as the value of transient impedance decreases as the humidity and the voltage level increases. From Table 8-a and b, it can be interpreted that a reduction in transient impedance value doesn't mean necessarily a better reduction rate in higher voltages. Table 9-b shows the average reduction rates for both materials are closed thus the similar safety levels can be applied for bentonite and the natural enhancement at H=72%.



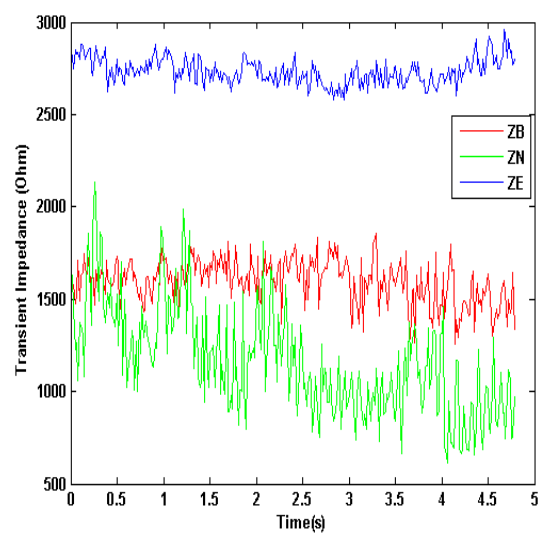
a



b



c



d

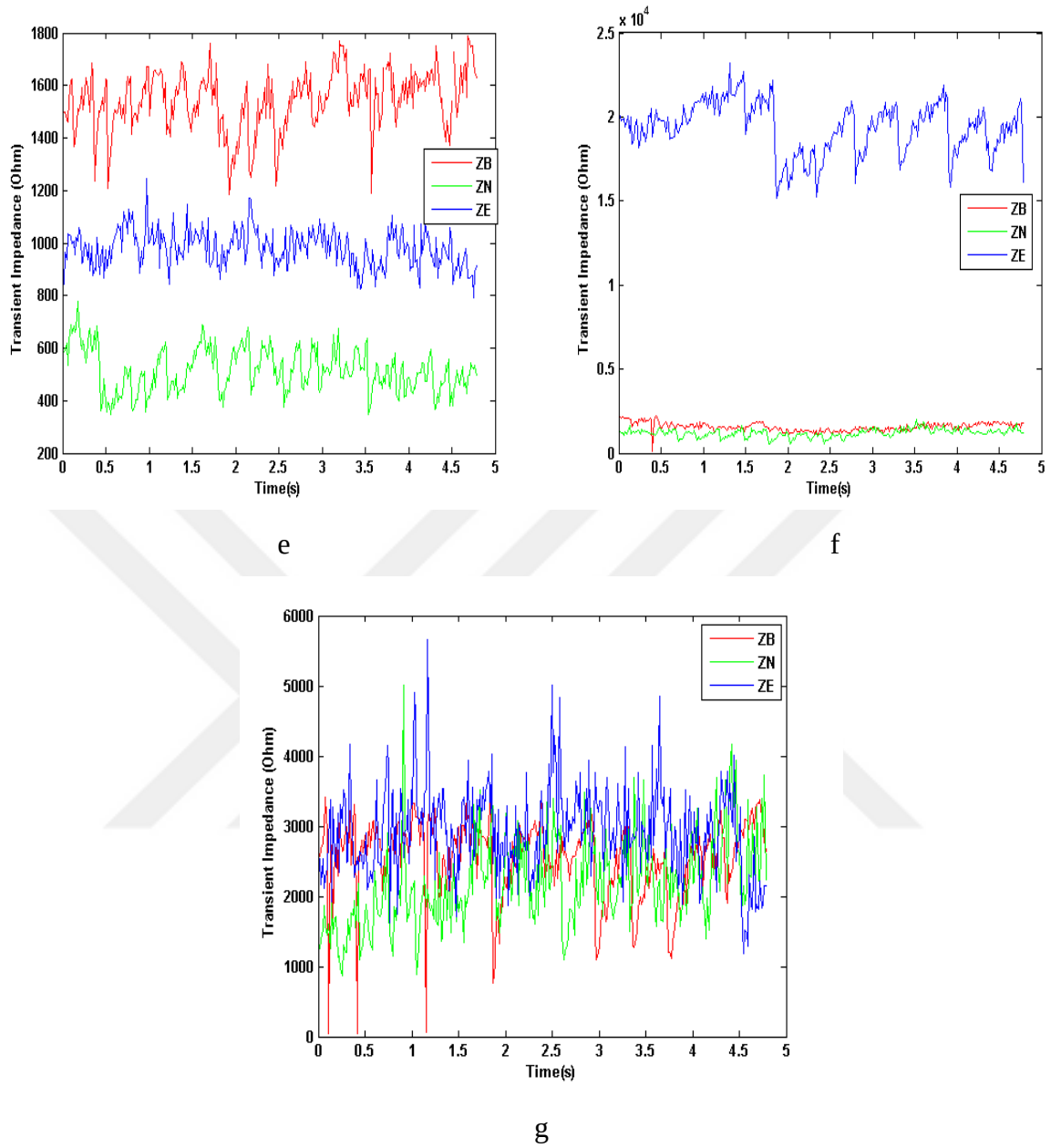


Figure 3.4: Transient impedance for 3 different rods at H= 75% a=856 V b=1054 V c=1465 V d=2050 V e=2670 V f=2900 V g=3760 V

Figure 3.4. a at V= 854V & H=75%, ZN, and ZB remain low and close values of $1\text{ k}\Omega$ and $1.1\text{ k}\Omega$ versus $62\text{ k}\Omega$ for ZE. Their K1 and K2 are 2.42% and 1.77% respectively.

Figure 3.4.b ZN and ZB behave linearly. They both register a high reduction rate of 0.63% and 0.88% for the bentonite and enhancement material

In Figure 3.4.c the value of soil transient impedance ZE dropped to $3.25\text{ k}\Omega$. 46.15% and 40% were registered for K1 and K2 respectively. The small upper hand for the natural enhancement material

Figure 3.4.c and d both show similar results. The values of the transient impedances are closed to each other. Consequently, the percentage of soil impedance reduction is weak. $K1=61\%$ and $K2=43\%$.

Figure 3.4.e ZB is higher than ZE. This may be because of the high hygroscopic aspect of the material, our NGEM has lower impedance and the bentonite got a higher transient impedance. ZN reached the lowest value of 600Ω and ZE 1.2Ω .

In Figure 3.4.f, ZN, and ZB kept low values but transient of the soil ZE rose to $20k\Omega$. Thus, $K1$ and $K2$ recorded a high reduction rate of 1.50% and 1% for the bentonite and the natural enhancement material.

Figure 3.4.g both the humidity and the voltage levels increased, the difference between the transient impedances of materials proposed is similar in general but our NGEM has a slightly better performance than the bentonite and the earth.

Table 10: a) Impedance for all voltages at $H=75\%$

b) The percentage of the impedance of reduction with respect to the ZE at $H=75\%$.

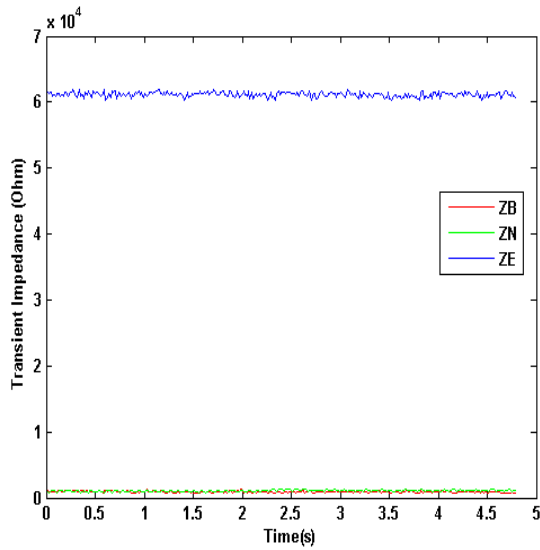
Volt(V)	ZB(k Ω)	ZN(k Ω)	ZE(k Ω)
854	1.5	1.1	62
1054	0.5	0.7	80
1465	1.5	1.3	3.25
2050	1.7	1.2	2.8
2670	1.6	0.6	1
2900	0.3	0.2	20
3760	NA	NA	NA

a

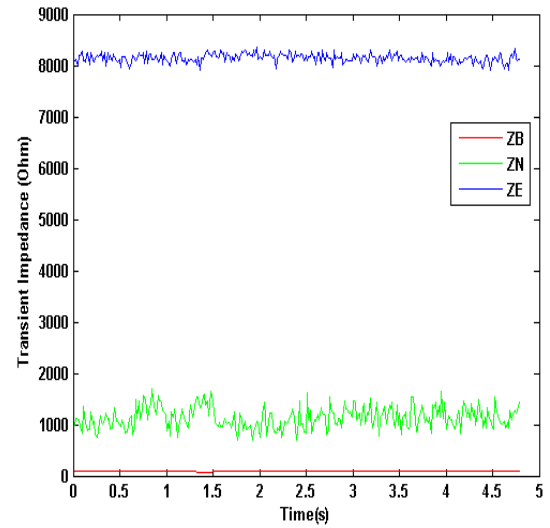
Volt (V)	854	1054	1465	2050	2670	2900	3760	AVG
K1 %	2.42%	0.63%	46.15%	60.71%	160.00%	1.50%	NA	83.08%
K2 %	1.77%	0.88%	40.00%	42.86%	60.00%	1.00%	NA	29.10%

b

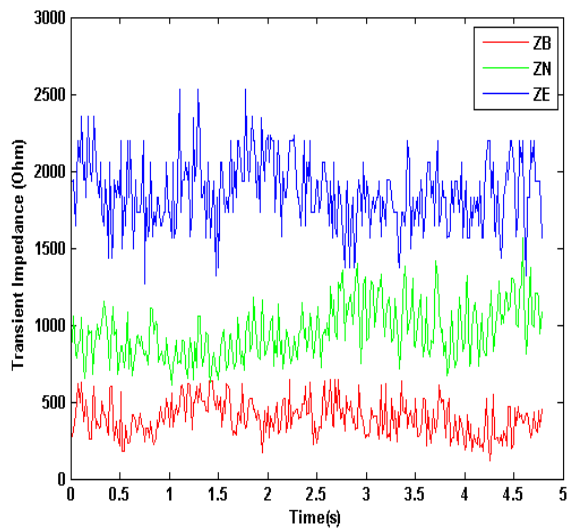
From Table 10-b, the average K1 and K2 gap are too big. The difference of 50% of the average reduction rate shows that different safety levels should be applied for bentonite and the natural enhancement material. The natural enhancement material is the safest at H=75%.



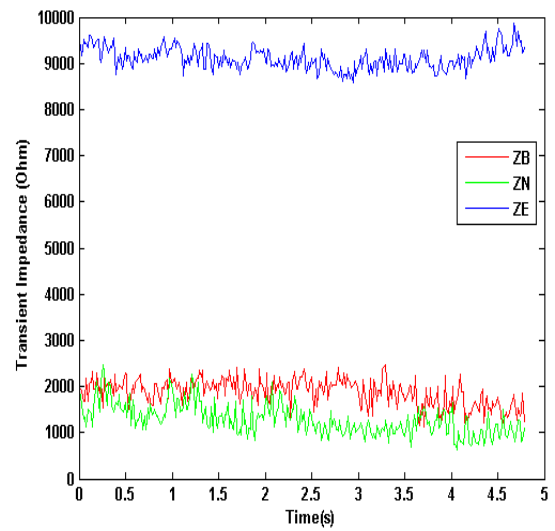
a



b



c



d

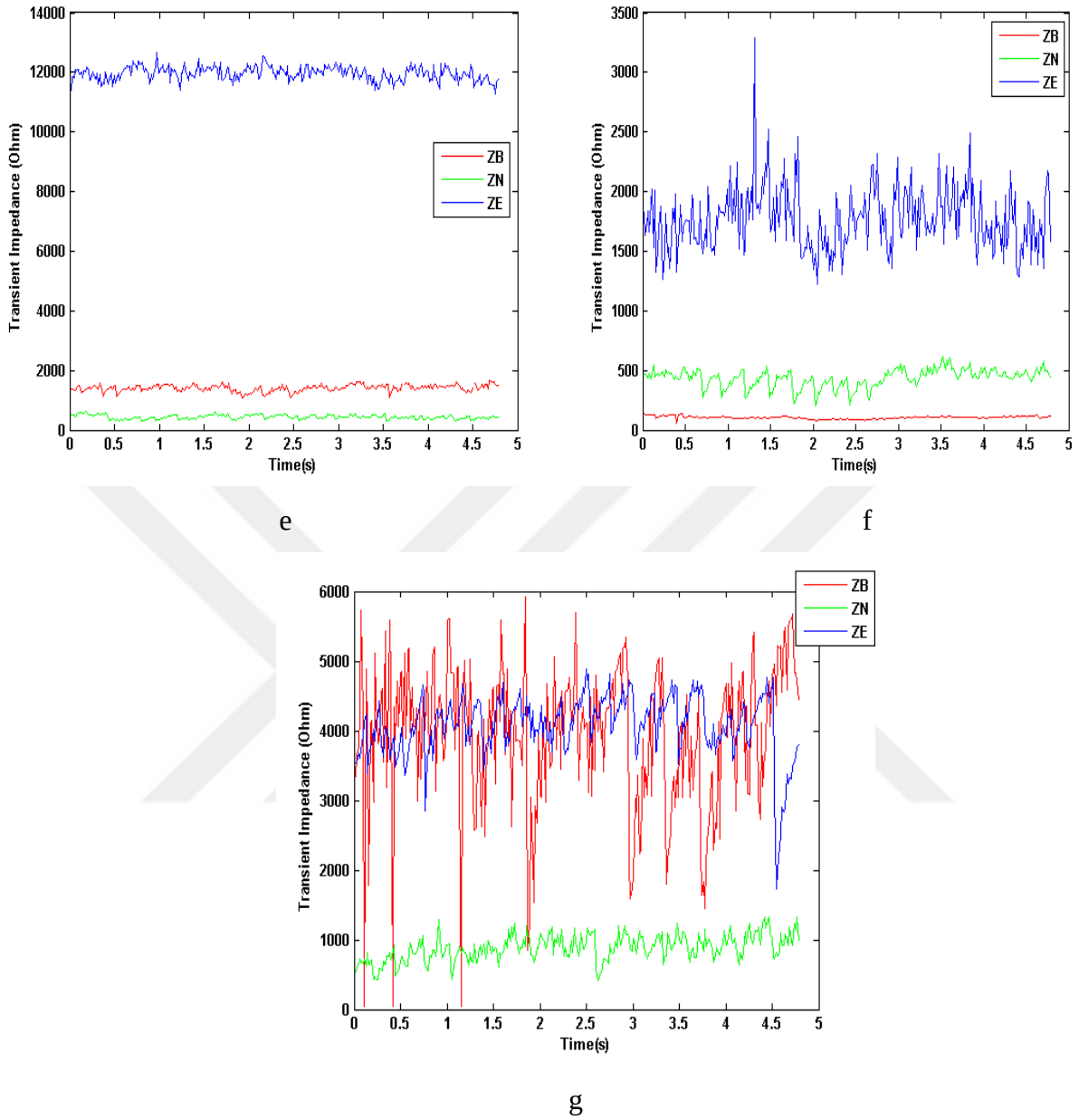


Figure 3.5: Transient impedance for 3 different rods at H= 76% a=856 V b=1054 V c=1465 V d=2050 V e=2670 V f=2900 V g=3760 V

In Figure 3.5.a, the gap between ZE and the transient values for the ground enhancement materials is very large. That proves in high humidity condition, both materials are very efficient with $K1=K2=1\%$.

In Figure 3.5.b, for $V=1054V$, a drop in transient impedance is recorded. ZB reached $0.4\text{ k}\Omega$ and ZN a $1\text{ k}\Omega$. A low soil impedance means a lower transient impedance reduction rate. The bentonite and natural enhancement material efficiency is very similar.

Figure 3.5.c the transient impedances for enhancement materials have not changed but ZE has dropped to 2 k Ω . A reduction of 20% and 50% are obtained for the bentonite and the natural material respectively.

Figure 3.5.d contrary to the figures above, we observe a spike in impedances for all the materials. ZB and ZE have similar transients' impedances. The reduction rate for the bentonite hasn't changed; the natural enhancement has performed much better than at V=1465V.

In Figure 3.5.e ZN has the lowest impedance with an impedance reduction rate (K2%) of 6.67% versus 12.50% for the bentonite.

Figure 3.5.f ZB and ZN are respectively 0.2 and 0.5 k Ω and the K1 and K2 registered 1.67% and 4.17% respectively.

In Figure 3.5.g ZN remains the same as in figure 53 ZB and ZE both register transient impedance values of 4 K Ω .

Table 11: a) Impedance for all voltages at H=76%

b) The percentage of the impedance of reduction with respect to the ZE at H= 76%.

Volt(V)	ZB(k Ω)	ZN(k Ω)	ZE(k Ω)
854	0.8	0.7	60
1054	0.4	1	80
1465	0.4	1	2
2050	2	2	9.4
2670	1.5	0.8	12
2900	0.2	0.5	12
3760	3	0.5	3.5

a

Volt (V)	854	1054	1465	2050	2670	2900	3760	AVG
K1 %	1.33%	0.50%	20.00%	21.28%	12.50%	1.67%	85.71%	20.43%
K2 %	1.17%	1.25%	50.00%	21.28%	6.67%	4.17%	14.29%	14.12%

b

Table 11-a, ZB, and ZN decrease uniformly as the voltage increases. The values of the transient's impedance of bentonite and the natural enhancement don't change much. Table 10-b shows a similar reduction rate for both materials. The bentonite and the NGEM have 14.12% and 20.43% average impedance reduction rate. Similar safety levels can be applied to both of them in the ground system.

The observation from all the humidity levels shows high efficiency in the proposed natural enhancement mixture capability to reduce soil transient impedance. It shows a similar impedance reduction rate to the bentonite.

Although there is an obvious reduction of ground transient impedance, it can be seen some uncorrelated variation of the impedance graphs. This effect is because of the erosion of the Cu rod (which was buried for more than 9 months), and the nature of the experiment soil itself. The transient events are very sudden and overpowering phenomena. So, when the transient current doesn't find a quick impede path, it propagates and causes variable impedances through the system. As mentioned in the experiment set up, the experiment ground is considered corrosive with grounding resistance reaching up to 800 Ω .m.

The present study on bentonite and natural enhancement material reveals a high reduction of transient impedance for the soil around the rod. In low humidity case, natural enhancement material seems to be more effective and much cheaper than the bentonite. The size of the grains in the bentonite and natural enhancement material is much smaller than the soil's grain size. From that observation; the resistivity ρ of bentonite and the natural enhancement material is much lower than the one of the soils, thus their current densities J would be higher under impulse voltage condition.

$$E = \rho * J$$

Hence, phenomena around the grounding rod encase an ionization in the ground enhancement materials.

The results of the investigation are similar to the behaviors in the article [16]. For the positive polarity impulse voltage, findings through this study also prove:

- An increase in voltage results in a decrease in soil impedance.
- Bentonite works better in a high moisture environment.

- Proposed natural enhancement mixture performance as good as bentonite under many voltages and humidity levels.

3.2 DWT Analyses

To understand the behavior of fault current flow in the soil, the same test current on the rods, which were buried in different types of soils is applied. The measurements are conducted within 4,8 s duration by using Discrete Wavelet Transform (DWT) to investigate the behavior of current. Time-domain representation is needed to know the duration of the fault current and to see the changes in the signal. Current signals recorded during the experiment for the voltage level [2050 V -3760 V] have been used for the simulation. The current signals were decomposed using DWT with a db4 mother wavelet. The analysis was up to level 3. The detail and the approximation coefficients at level 3 for the voltages are plotted for each humidity level. A closer look at the higher frequency information d1 indices will be used to locate the time and the amplitude of fault during the measurement time

Note that NG means natural enhancement material, cur NG represents the current for natural enhancement material and cur Ben represents the current for bentonite. This high peak and the number of readable peaks is used to detect faults, and the time they happen in the electrical system.

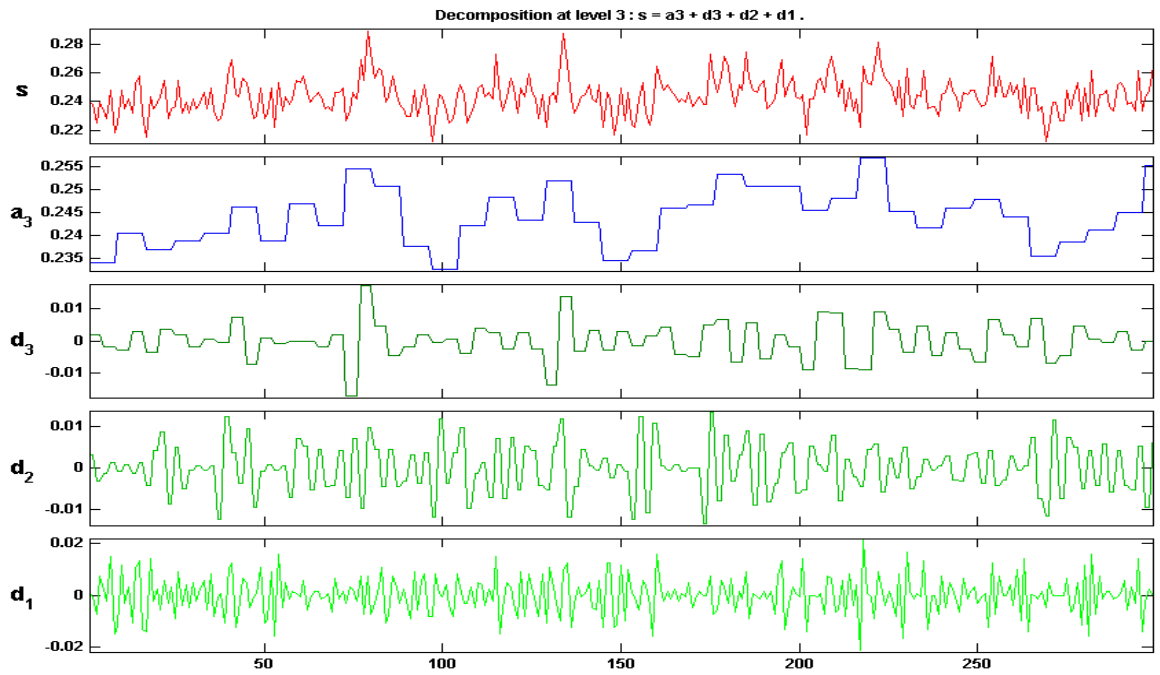


Figure 3.6: DWT based decomposition of the dissipated current signal in the soil for bentonite at V=2050 V & H=68%. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

The details coefficients for bentonite d1 and d2 present in Figure 3.6 shows weak discharge points. The discharge magnitude d1 varies between 20 mA and -20 mA.

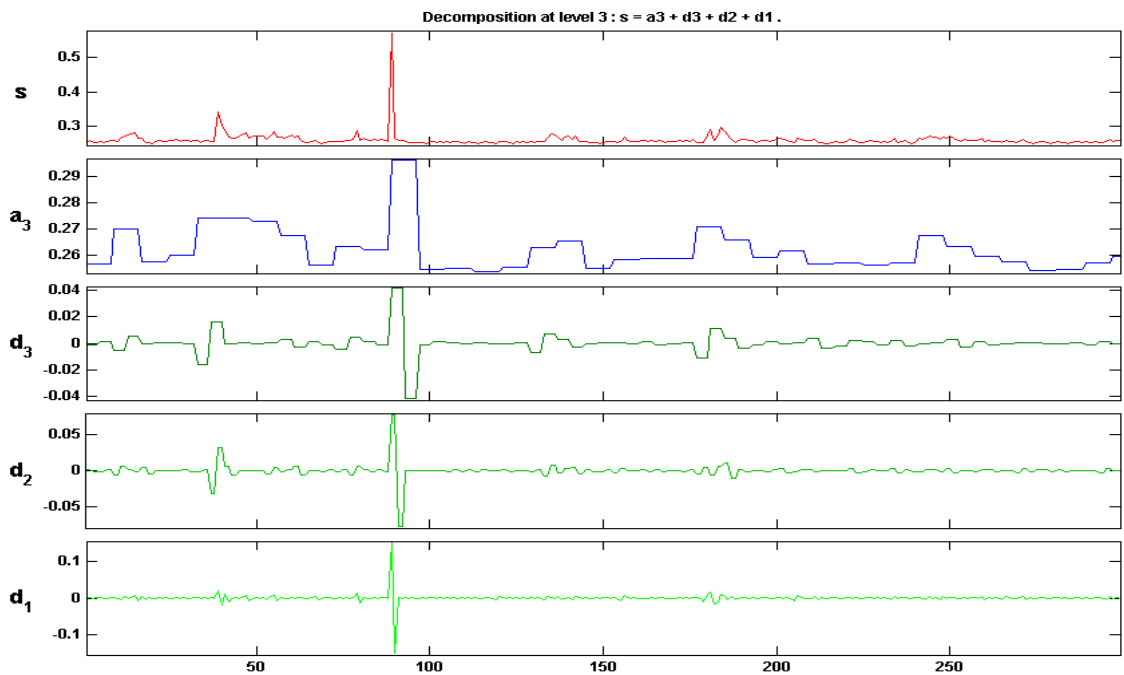


Figure 3.7: DWT based decomposition of the dissipated current signal in the soil for NG at V=2050 V & H=68%.

V=2050V & H=68%. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

The current magnitude varies between -0.1 A and 0.1 A with the presence of a discharge point. The discharge happens later after in the excitation precisely about $\frac{1}{4}$ of the total excitement time.

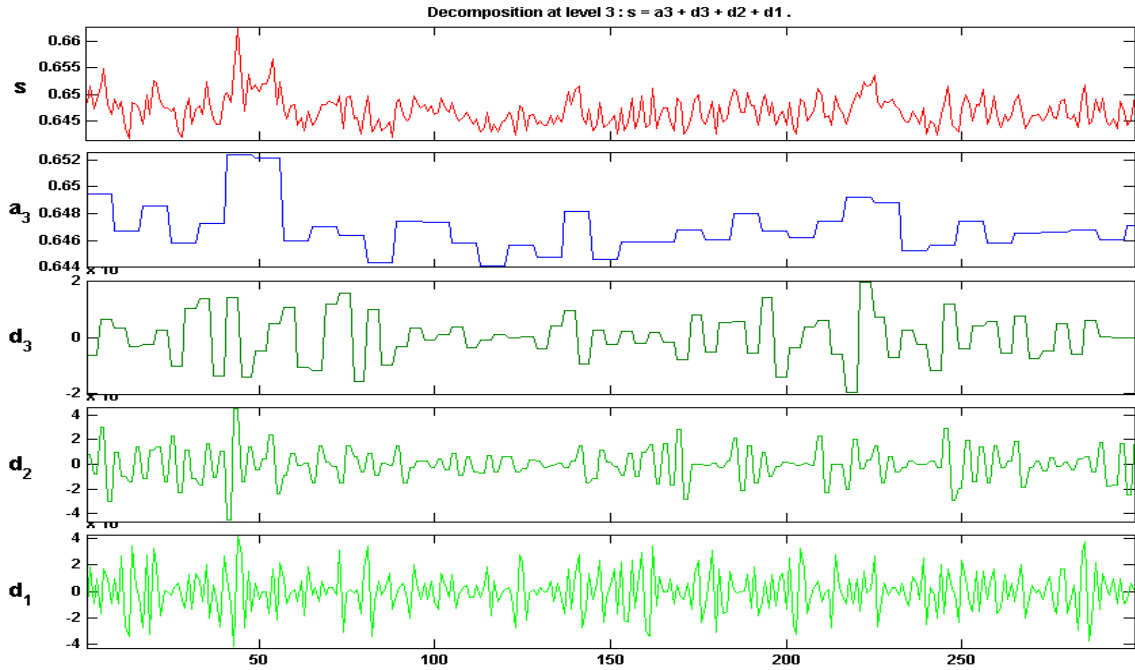


Figure 3.8: DWT based decomposition of the dissipated current signal in the soil for normal soil at V=2050 V & H=68%. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

The DWT decomposition coefficients d1, d2, and d3 in Figure 3.8 don't reveal much as the signal recorded has too much noise. Though d1 changes between 4 A and -4 A.

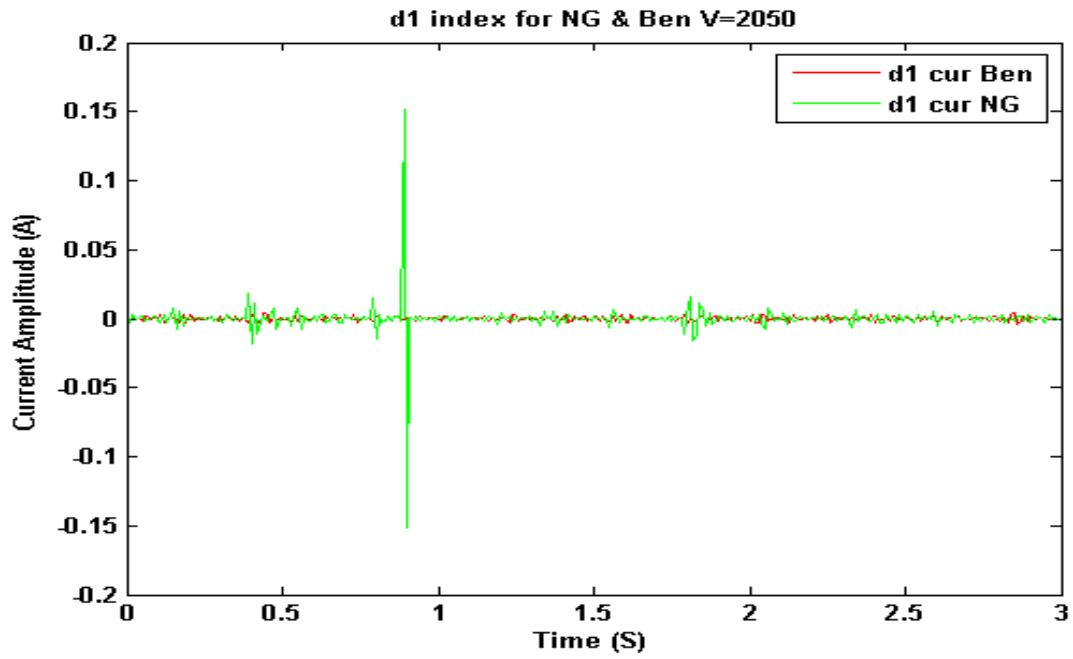


Figure 3.9: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at $V=2050$ V and $H=68\%$.

In Figure 3.9, d1 indices for bentonite and NG at $V=2050$ V are represented. The only discharge happened for the NG at $t=0.9$ s. The bentonite d1 can't be seen on Figure 3.9 because it is too small compared to d1 index of NG (Figure 3.7). The discharge time for the NG is quicker and the number of discharge points is also higher.

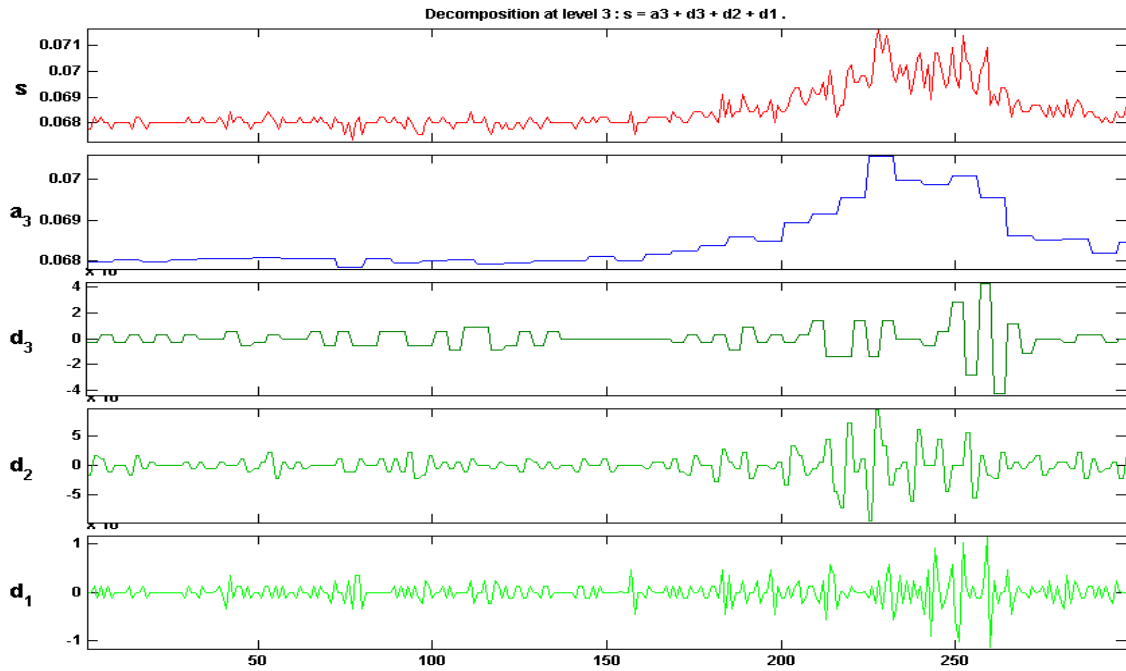


Figure 3.10: DWT based decomposition of the dissipated current signal in the soil for bentonite at V=2670 V & H=68%. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

The event corresponding to the detail coefficient d1 and d2 are illustrated in Figure 3.10. for bentonite. The values of the current flow are nearly zero except at the instant the current peak $t=3.8s$, $4s$ and $4.16s$ where d1 changes between 1A and -1A for a duration of 0.2s are observed. The oscillations in cur-bent happens extremely.

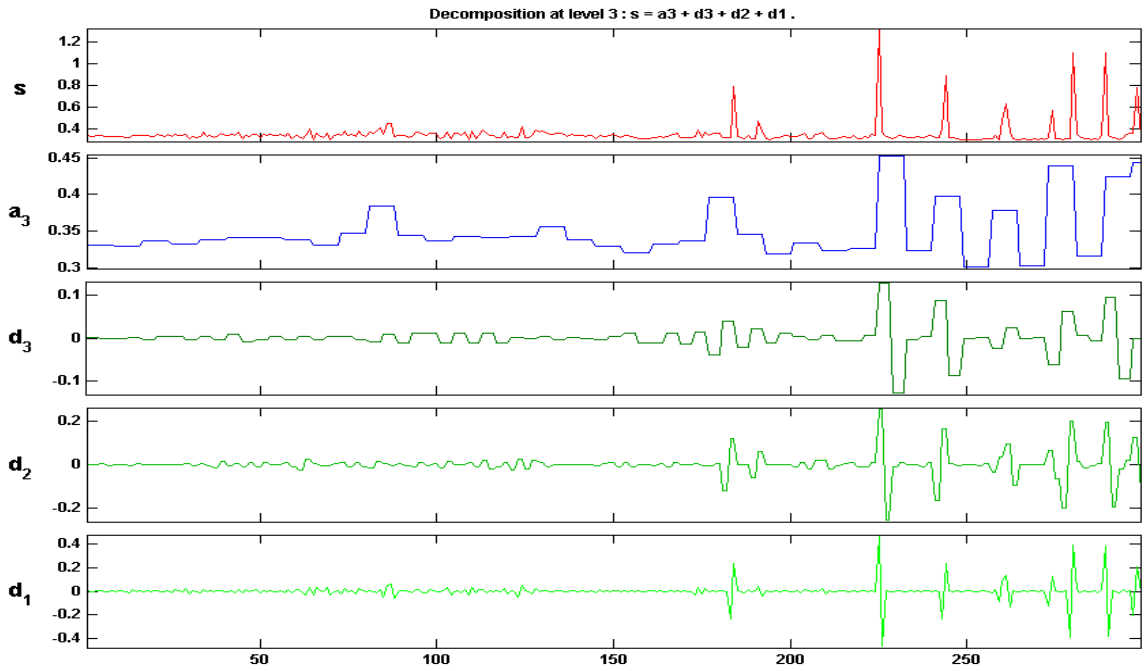


Figure 3.11: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2670$ V & $H=68\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

The events corresponding to the detail coefficient d1 and d2 are illustrated in Figure 3.11 for NG. The values of the current flow are nearly zero except at the instant the current peak where d1 changes between 0.4 A and -0.4 A for a duration of 0.2 s are observed. Multiple discharge points are present in the d1 index with different magnitudes. As in Figure 3.10, the oscillations start after 1.78 s the impulse voltage was given.

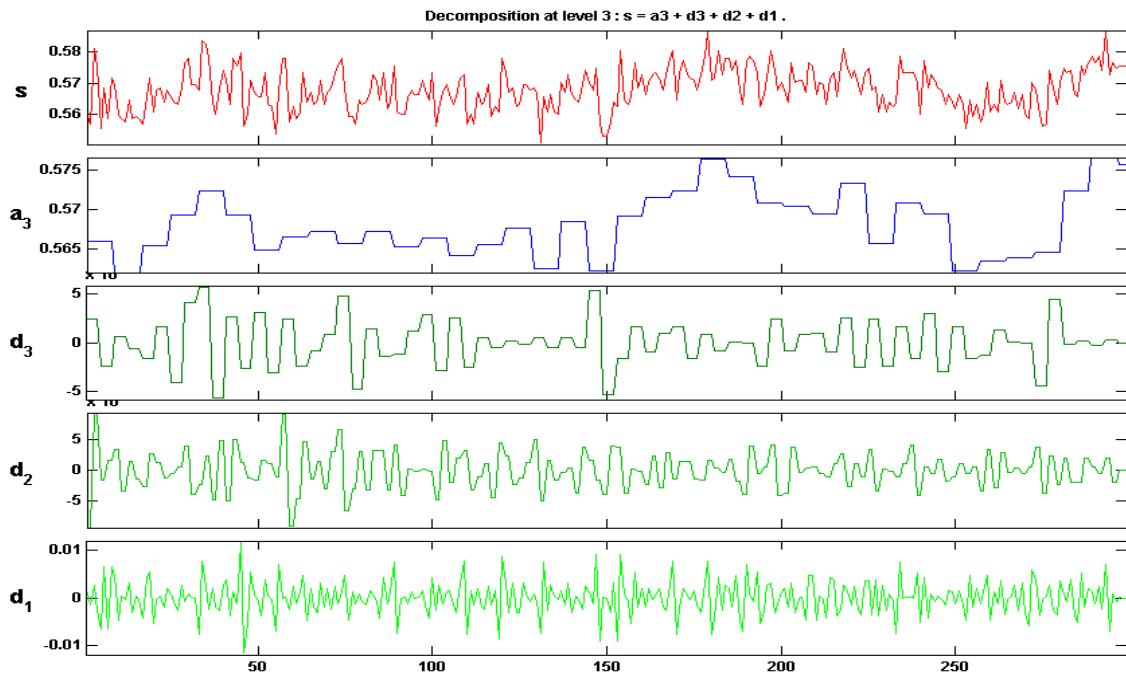


Figure 3.12: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2670$ V & $H=68\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2. and 1. respectively.

A clear reading of the signal is not possible for Figure 3.12 because of the excessive noise presents in the signal.

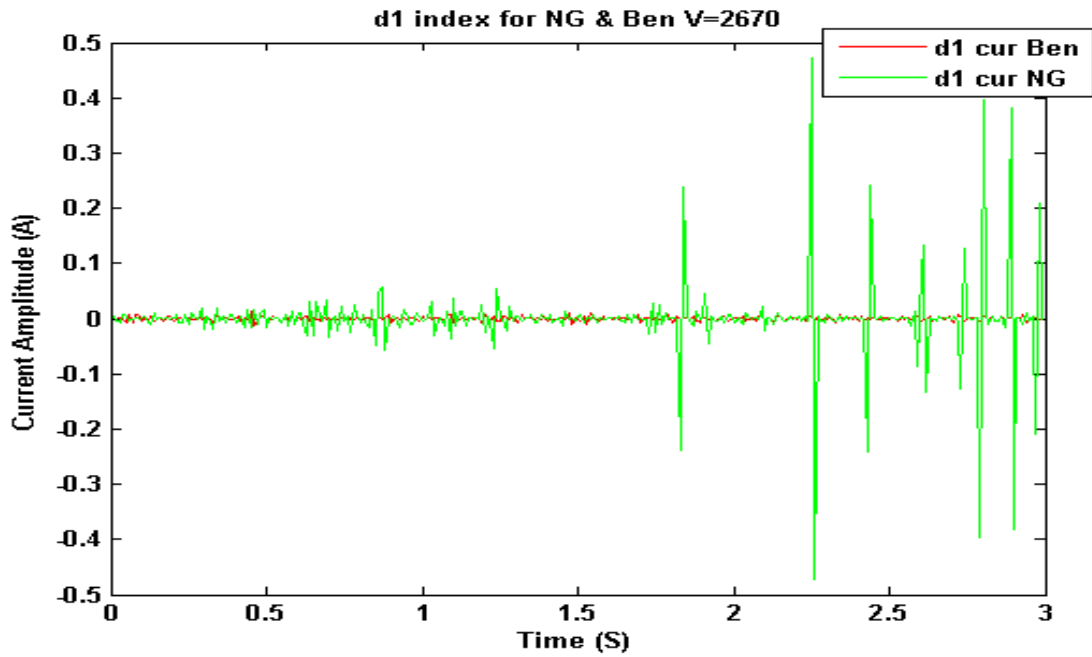


Figure 3.13: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=2670 V and H=68%.

Figure 3.13 shows the different peaks observed for NG d1 index. The highest discharge happened at $t=2.25$ s followed by smaller peaks. Multiple discharges points can thus infer a quick dissipation fault current into the soil. The discharge for the bentonite starts at $t=3.8$ s which much later than the one for NG. The magnitude of NGEM discharge is higher and accompanied by fewer discharges' points. The data in Table 7 a support that observation.

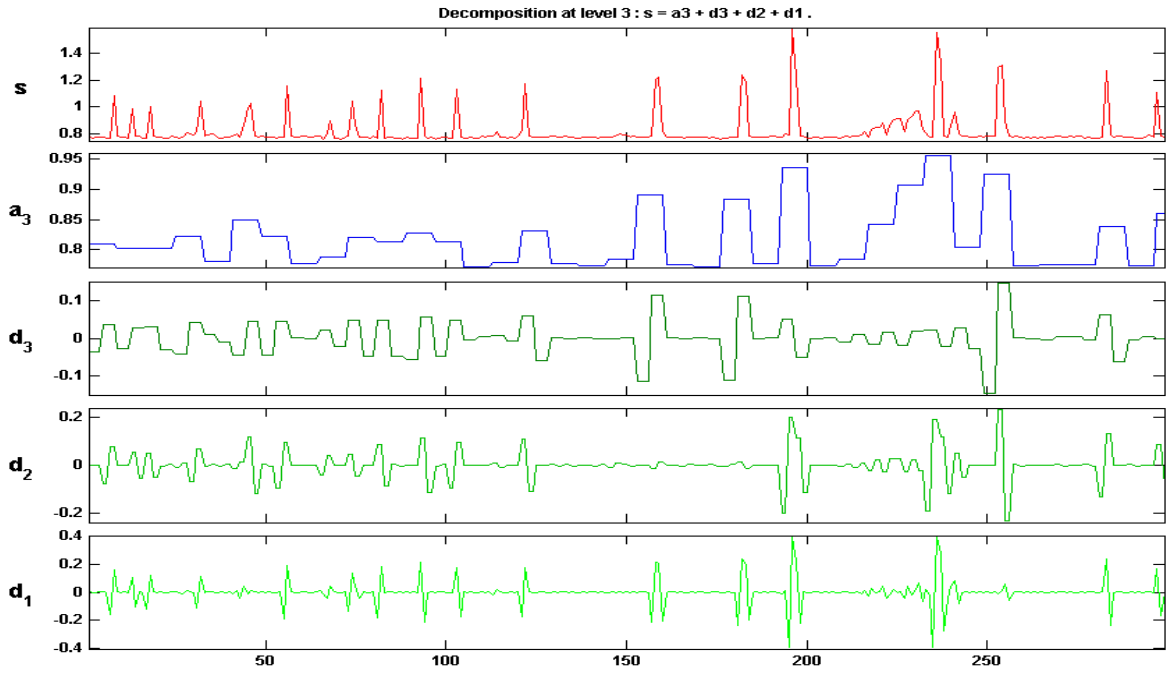


Figure 3.14: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=2900$ V & $H=68\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

In Figure 3.14, the events corresponding to the detail coefficient d_1 and d_2 are illustrated, for bentonite. The values of the current flow are nearly zero except at the instant the discharges, where d_1 changes between 0.4 A and -0.4 A. The magnitude of the fault currents have increased compared to the previous Figure 3.10.

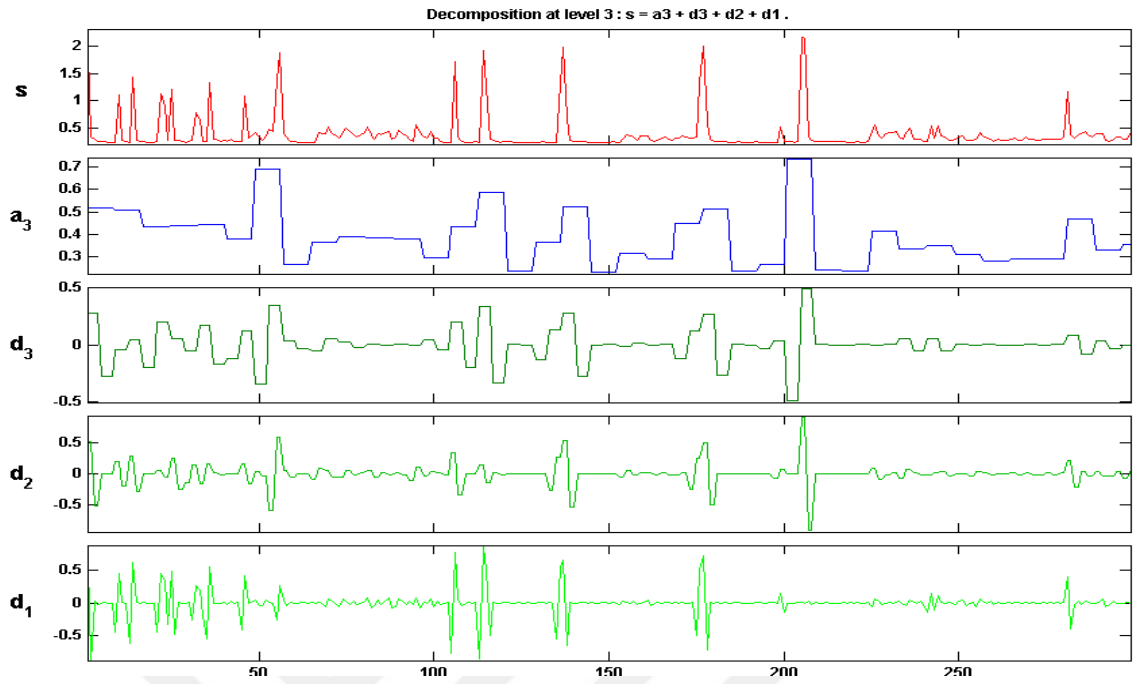


Figure 3.15: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2900$ V & $H=68\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

In Figure 3.15, d1 index for NG reveals multiple discharge points of various amplitudes. Earlier discharge point is seen since $t=0.05$ s with the highest amplitude of 1 A. Along the rest of the excitation time, various peak points are recorded varying between 0.5 A to 1 A at different time.

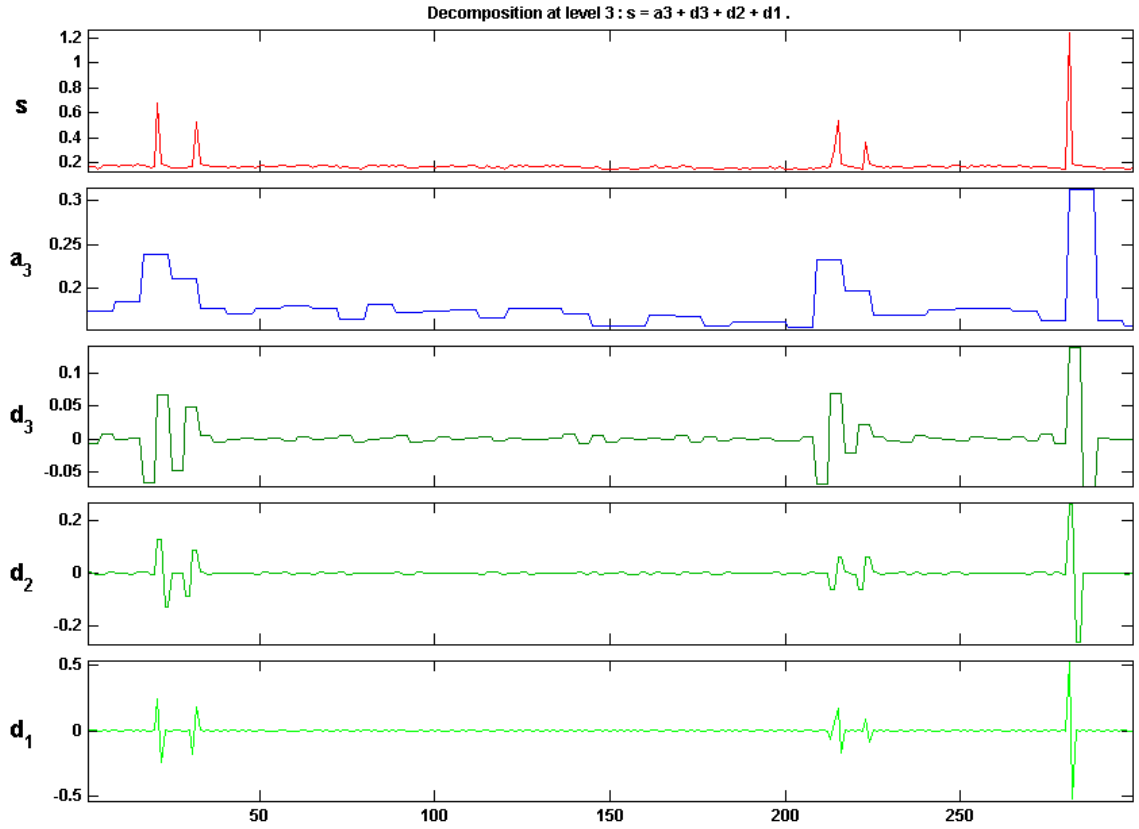


Figure 3.16: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2900$ V & $H=68\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. The soil d_1 index in Figure 3.16 shows a high discharge at exactly $t=4.16$ s. 3 Small peaks can also be detected at different intervals of time.

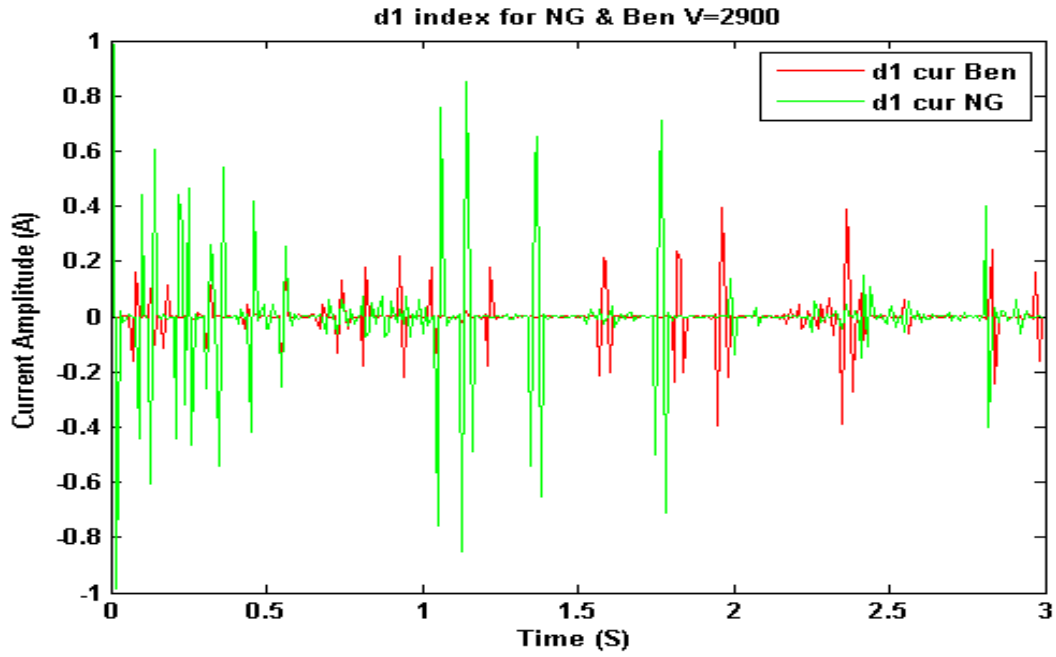


Figure 3.17: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=2900 V and H=68%.

The events shown in Figure 3.17, represent d1 coefficients for NG and the bentonite at V=2900 V. As shown in the graphs, multiple discharges fault currents in the soil are recorded with the highest happening at $t=0.1$ s the second highest at $t=1.1$ s with 1 A and 0.8 A respectively for the NG. The NG recorded the quickest and the high discharge current at $t=0.05$ s and consecutive various current amplitudes along the excitation time. At $t= 1.9$ s and 2.4 s the 2 highest equals magnitude of 0.8 A events are recorded for the bentonite. The bentonite response is slow and small discharge points are recorded.

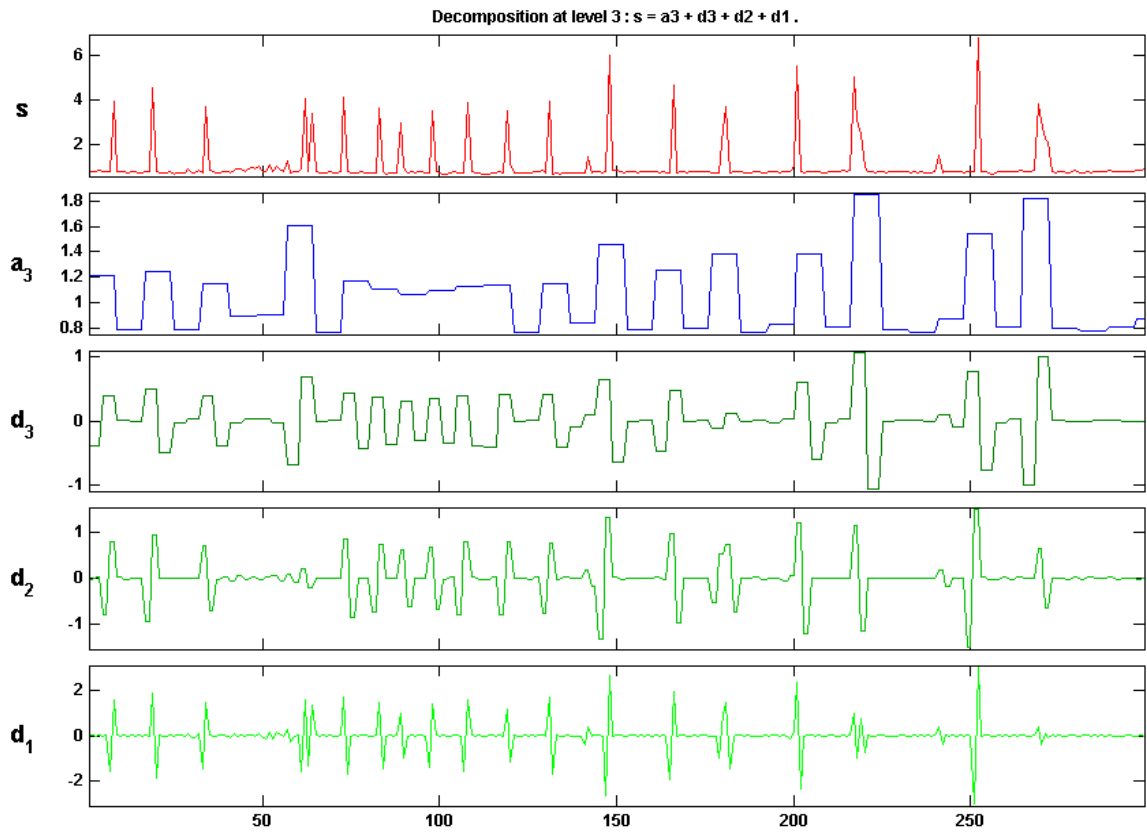


Figure 3.18: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=3760$ V & $H=68\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively.

The highest peak observed at $t=4.032$ s for an amplitude of 6.8 A and a duration 0.3s. The coefficient d_1 is varying between 2.5 A and -2.5 A as can be seen in Figure 3.18 at the moment of the pick. That is the case in which most of the current is dissipated into the ground. The early discharges of 2 A at $t=0.1$ s and 4 A at $t=0.2$ s are registered. This high peak is used to detect faults in the electrical system.

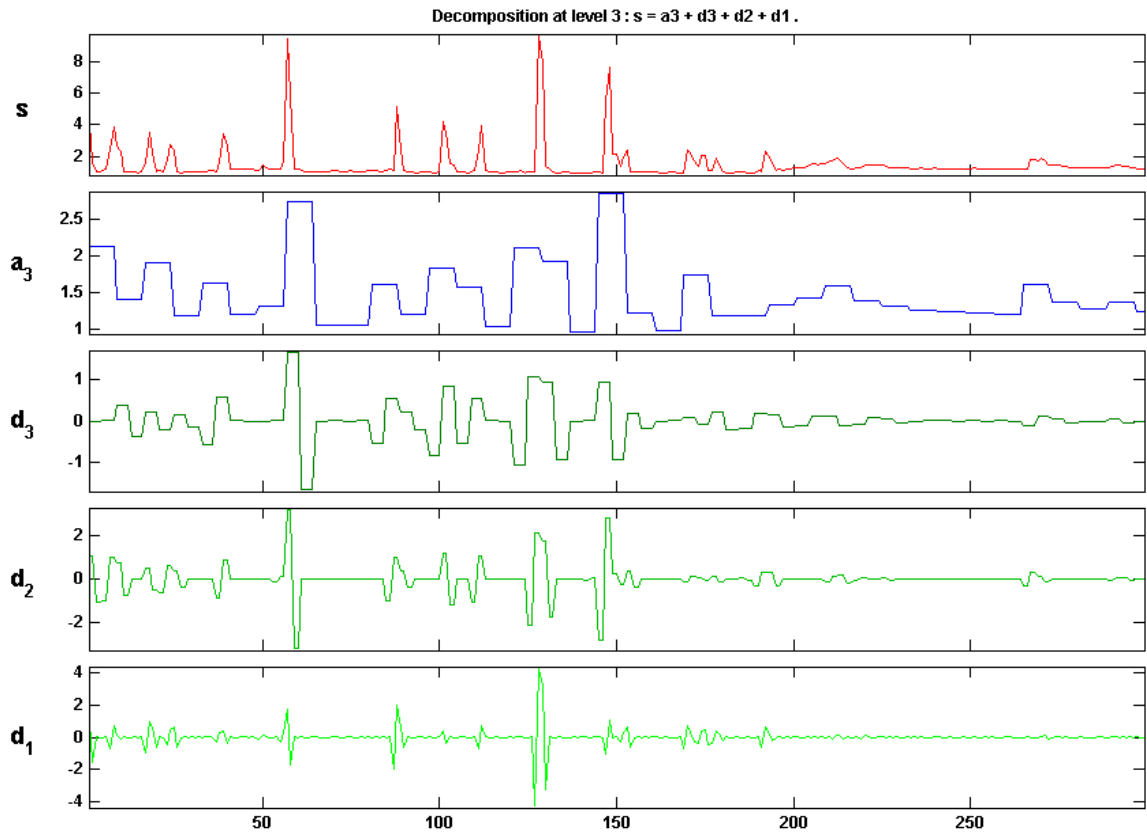


Figure 3.19: DWT based decomposition of the dissipated current signal in the soil for NG at $V=3760$ V & $H=68\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

The index corresponding to d1 of the current for proposed natural enhancement material is shown in Figure 3.19. Consecutive peaks of decreasing magnitudes happen after the highest peaks and die out. d1 and d2's highest peaks come at $t=1.25$ s and changes between 5A and -5 A. Besides those precise moments, the index value of the current is nearly zero but for some few discharges of amplitudes 2A and 2.5A. The highest pick duration is 0.182 s. From Figure 3.19 the natural enhancement natural peak discharges quicker than the bentonite peak.

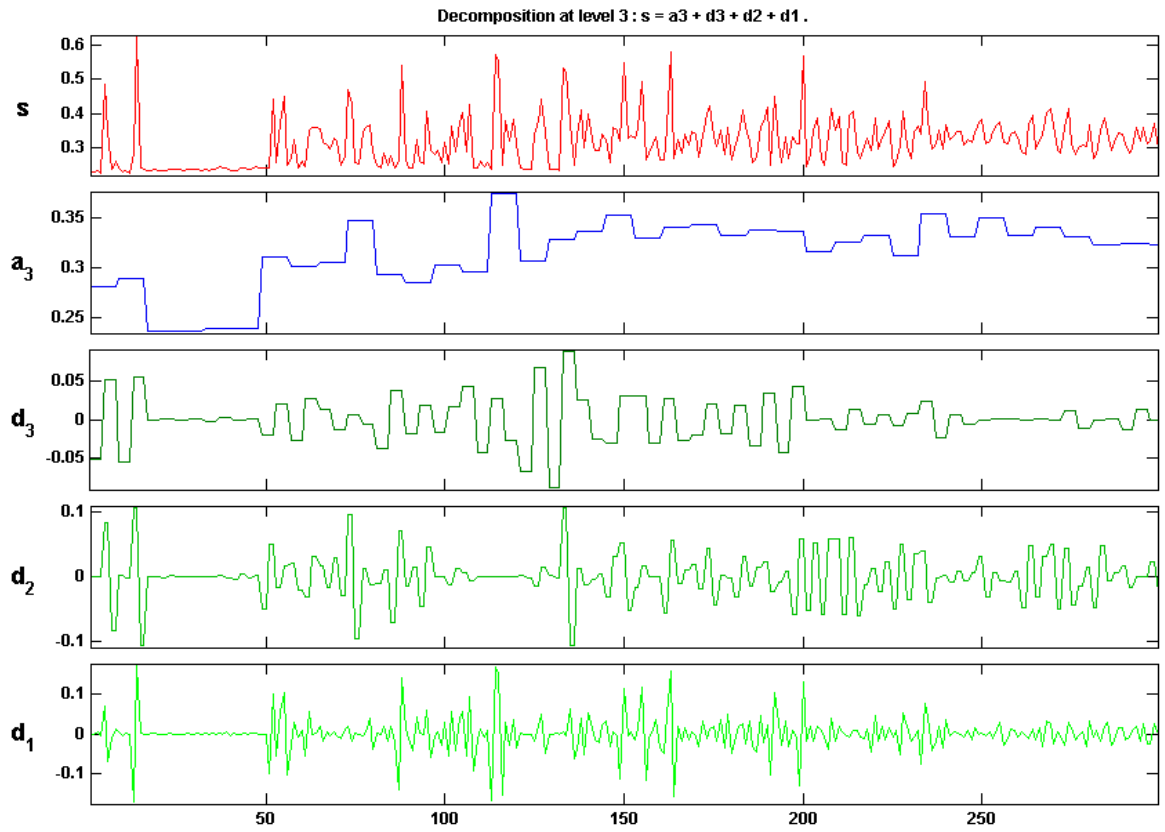


Fig 3.20: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=3760$ V & $H=68\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively. The first highest peak for the normal soil happened at $t=0.16$ s and the rest of the signal is considered to be noise.

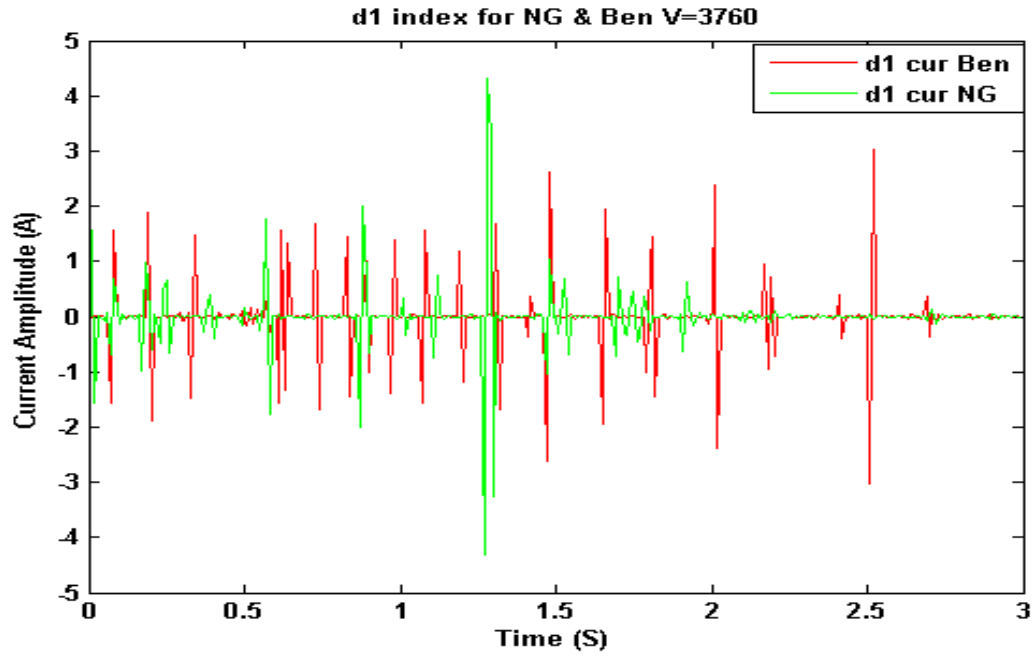


Figure 3.21: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=3760 V and H=68%.

The details coefficients for bentonite d1 and d2 present in Figure 3.21 shows multiple discharges over the 4.8s. The discharge magnitude d1 varies between 5A and -5A at t=1.3s to 3A at t=2.25s with the highest peak duration of 0.27s. Both of the signal's present multiple discharges long the excitation time with NG which shows the earliest at t=0.01s for 2 A. As concluded Table 7, the figures 3.6 to Figure 3.21 proves an increase in excitation voltage will consequently cause a decrease in soil transient impedance. At H=68%, NG clearly shows earlier and higher discharges paths compared to bentonite.

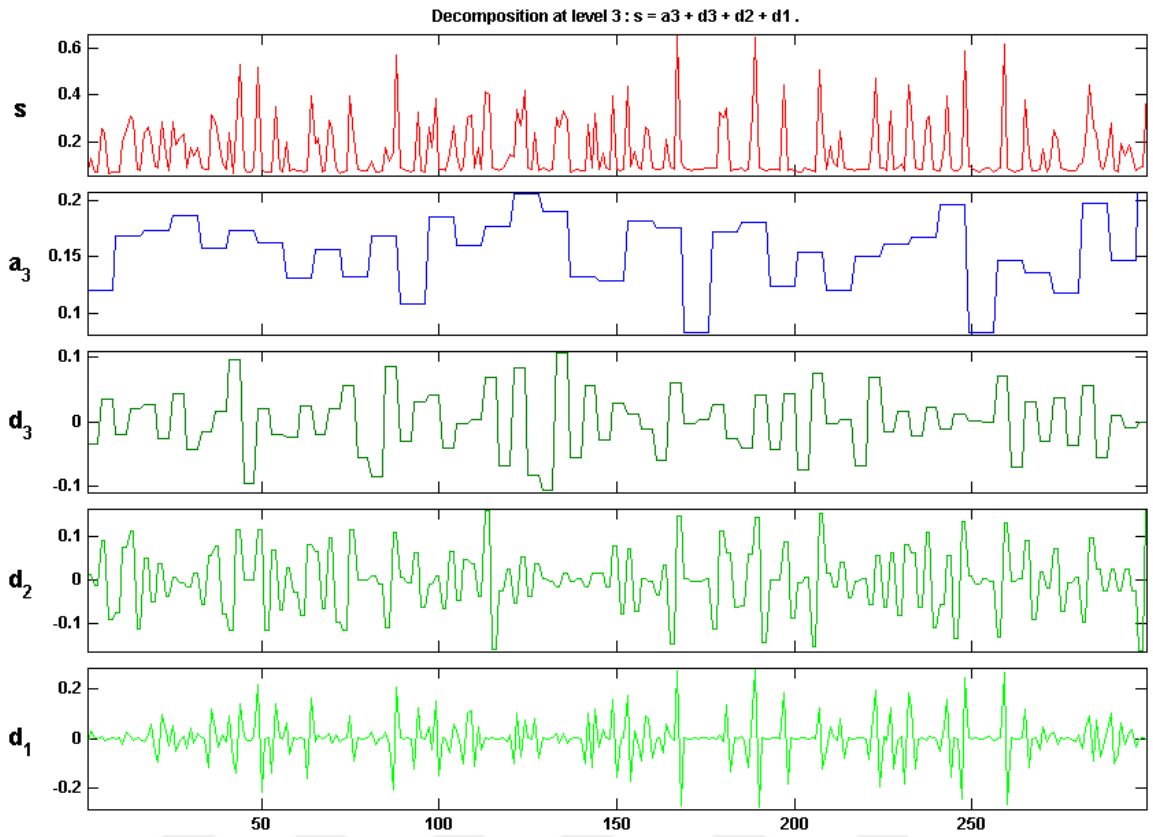


Figure 3.22: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=2050$ V & $H=70\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively.

In Figure 3.22, the amplitude of the signal varies 0.2 and -0.2 A. Various short and weak peaks are observed along the excitation time with the highest occurring at $t=1.8$ s.

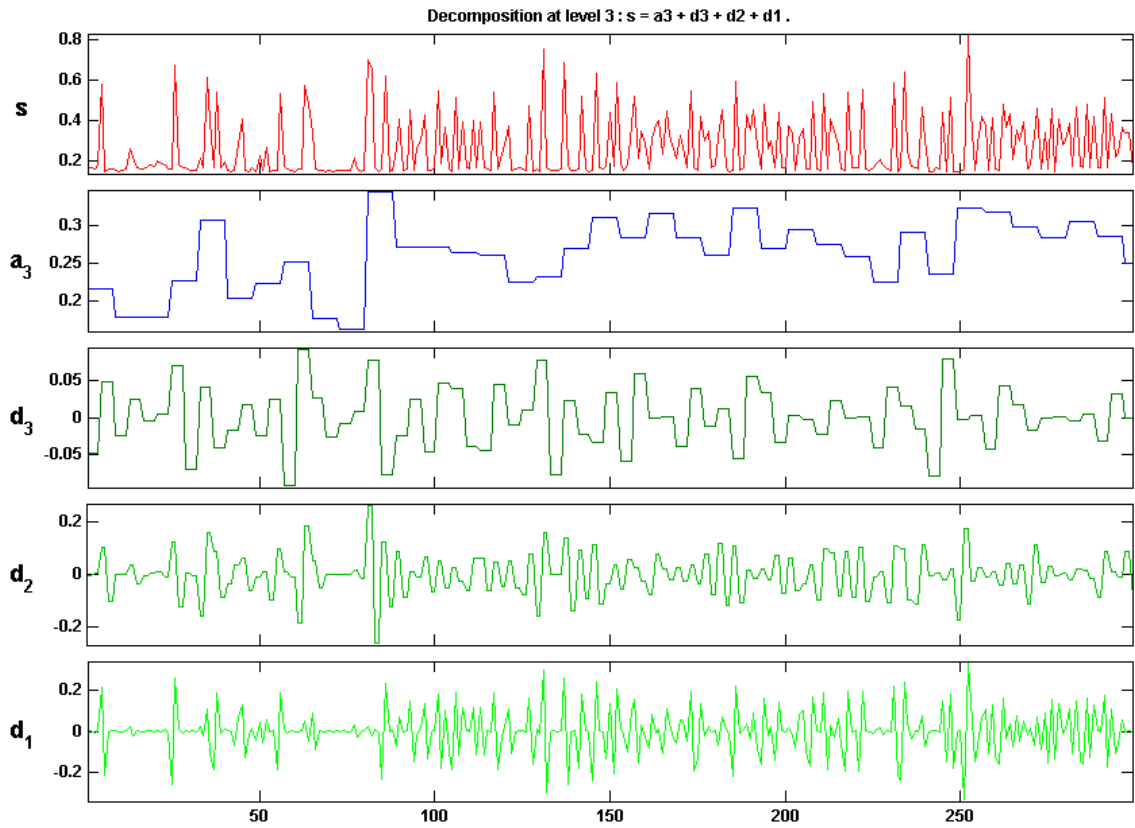


Figure 3.23: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2050$ V & $H=70\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. A clear lecture of the signal is possible for 1.2 s. The early discharges of amplitudes 0.2 A are observed at $t=0.1$ s and 0.3 s and some oscillations of different amplitudes are also observed.

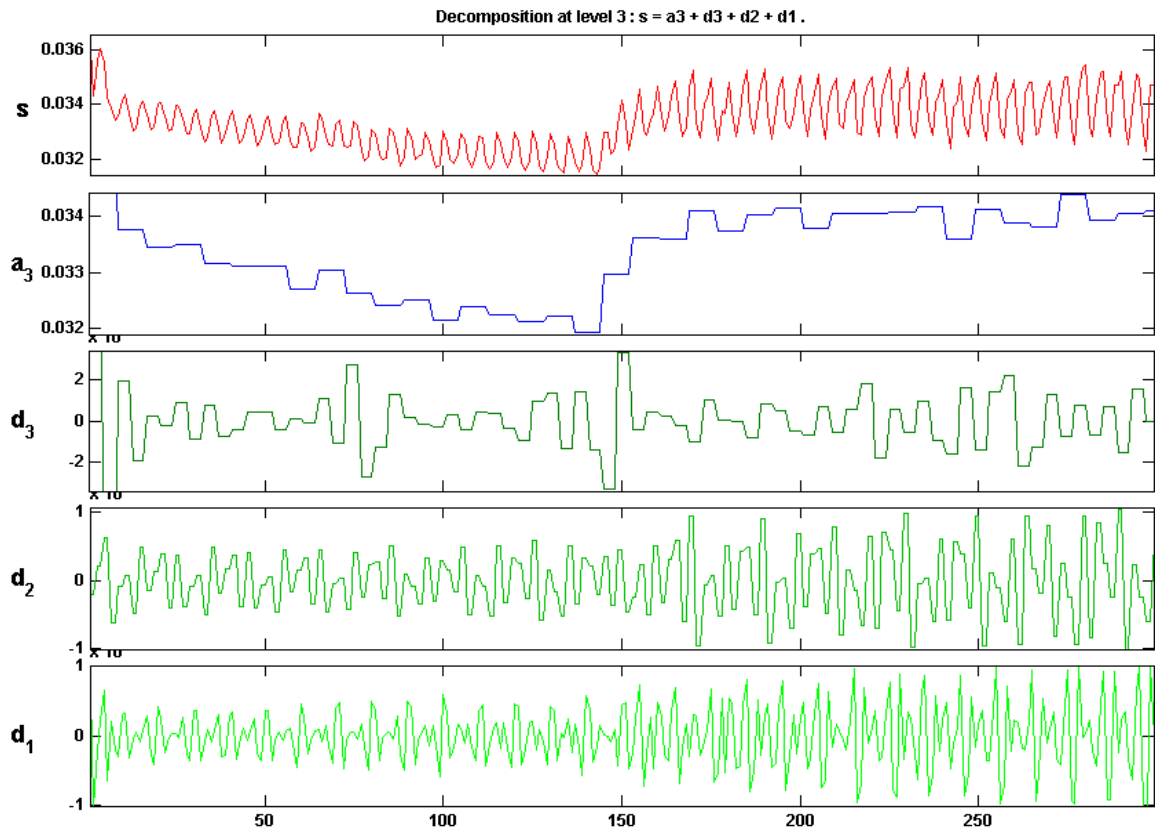


Figure 3.24: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2050$ V & $H=70\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively. Multiple oscillations are observed on the signal. The accurate reading is not possible because of the high noise in the signal.

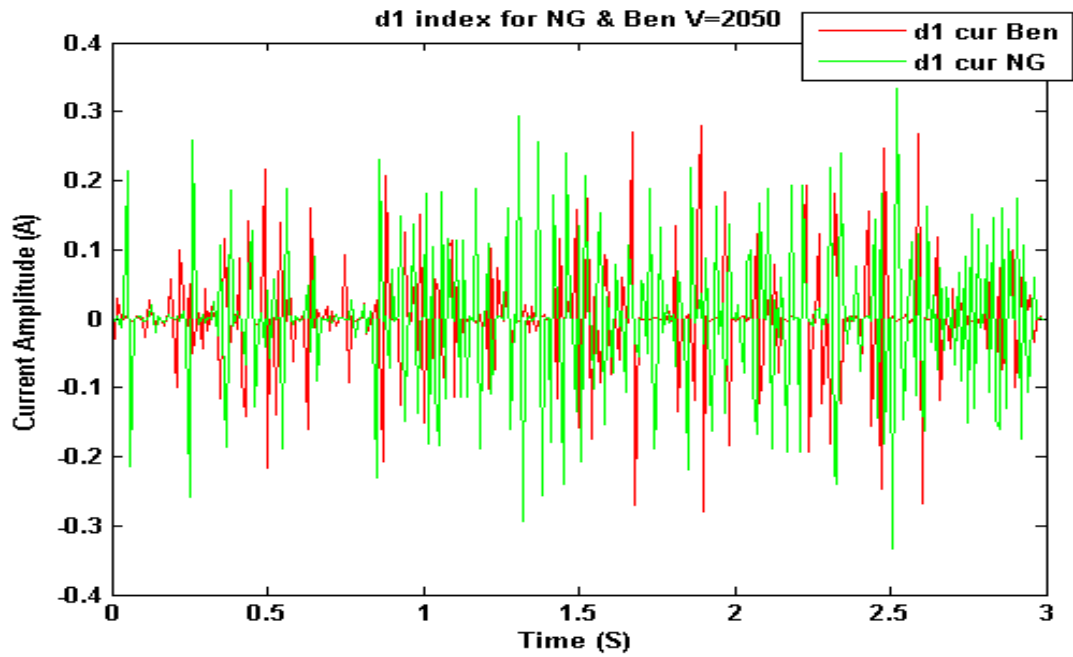


Figure 3.25: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at $V=2050V$ and $H=70\%$.

Figure 3.25 shows the combined d1 indices graphs for the bentonite and NG discharge currents. The earliest discharge happens at $t=0.08s$ for an amplitude of $0.2 A$ for the NG and the earliest peak for the bentonite $t=0.5 s$. Between $t=0.09 s$ and $t=2.75 s$ multiple oscillations for both materials are observed.

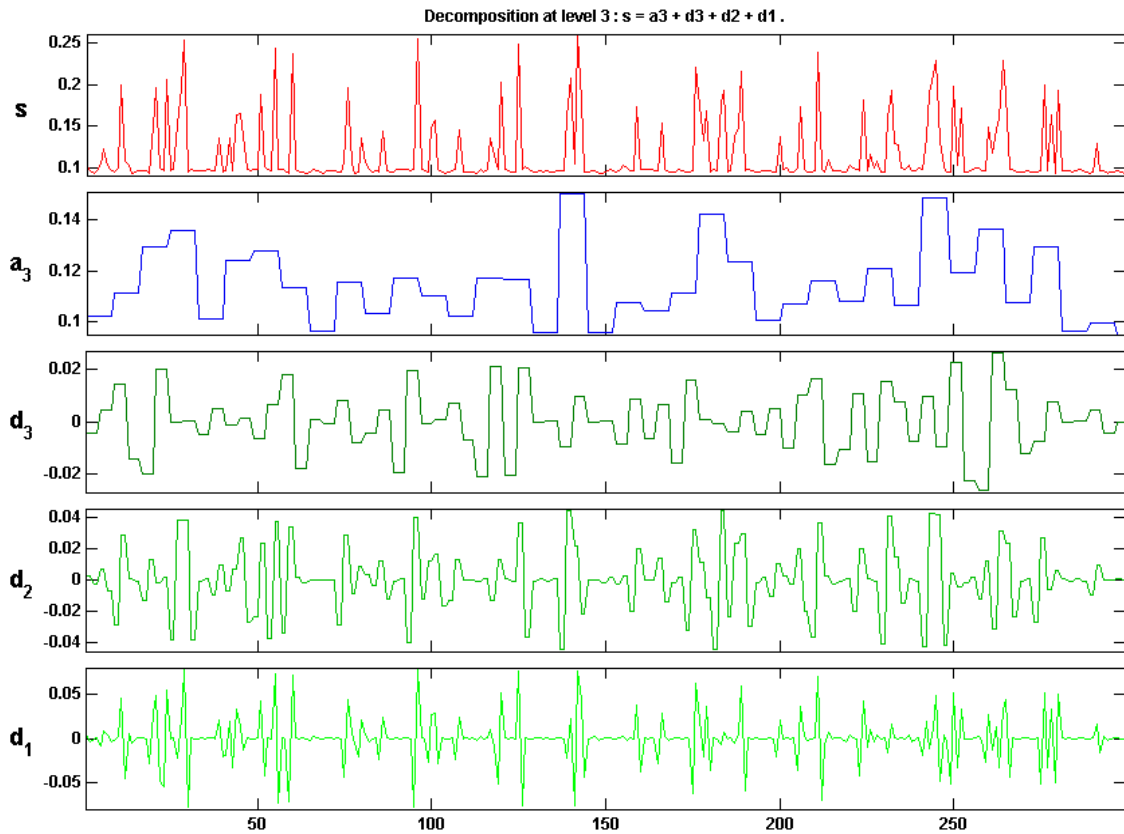


Figure 3.26: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=2670$ V & $H=70\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively.

Figure 3.26 current faults can be seeing in d_1 index. Different current amplitudes are observed varying between 0.05 A to -0.05A. Multiple discharges points are observed all along the excitation time.

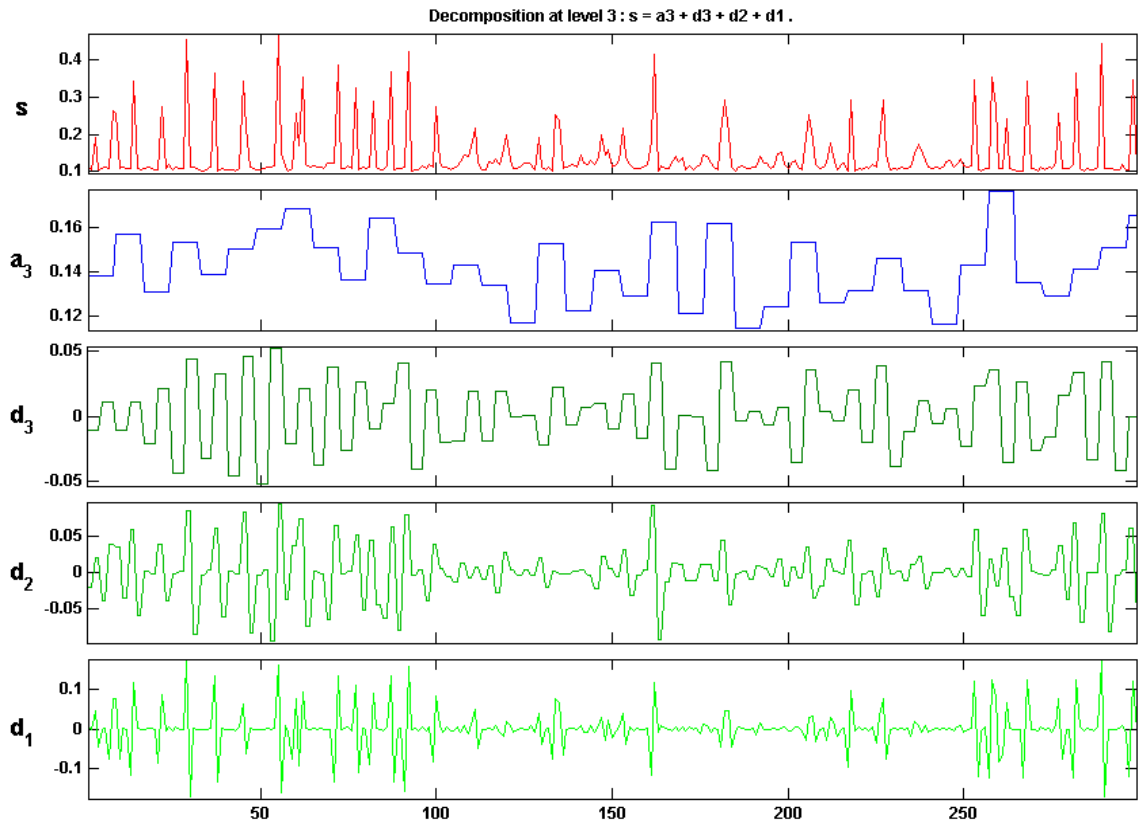


Figure 3.27: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2670$ V & $H=70\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively. Figure 3.27 events can be seen at the beginning and the end of the signal. The middle slowly dies out to zero and discharges up to 0.4 A are observed.

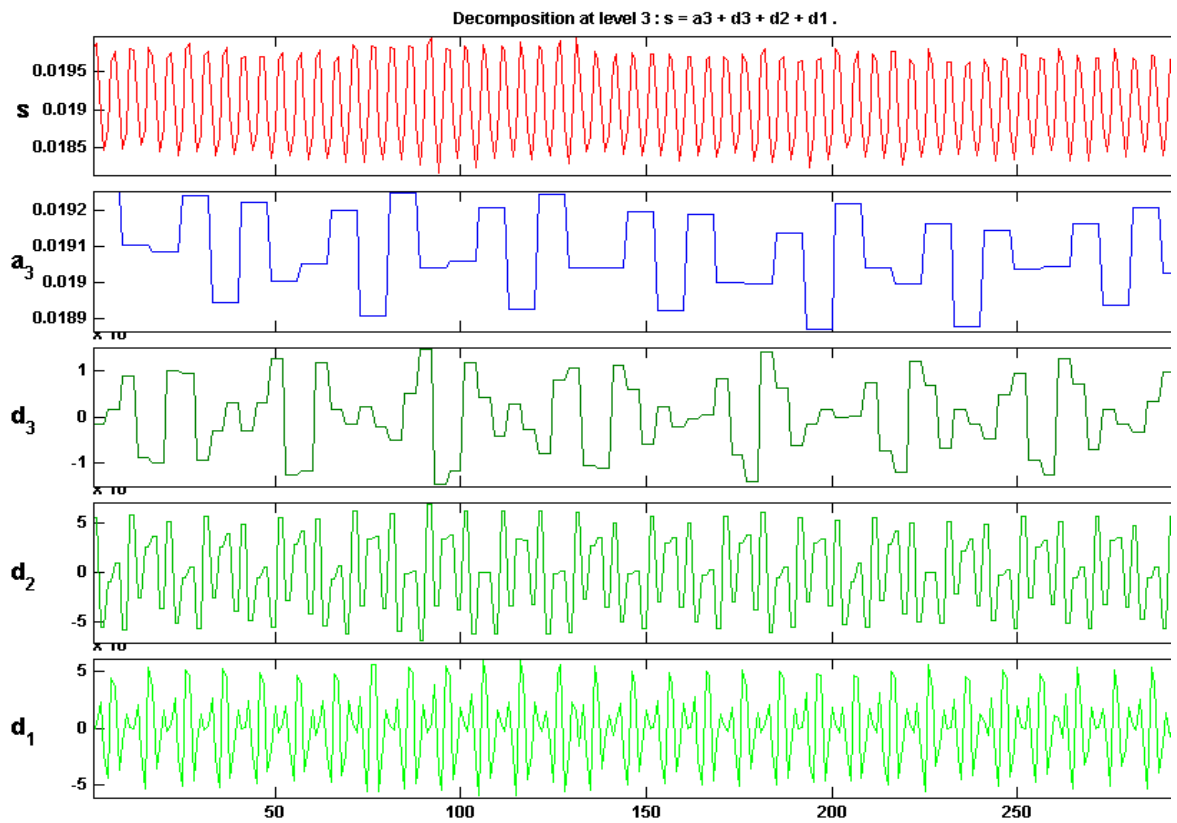


Figure 3.28: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2670$ V & $H=70\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively. No lecture is possible due to the noise as the signal is repetitive and the amplitudes change between 5A and -5 A.

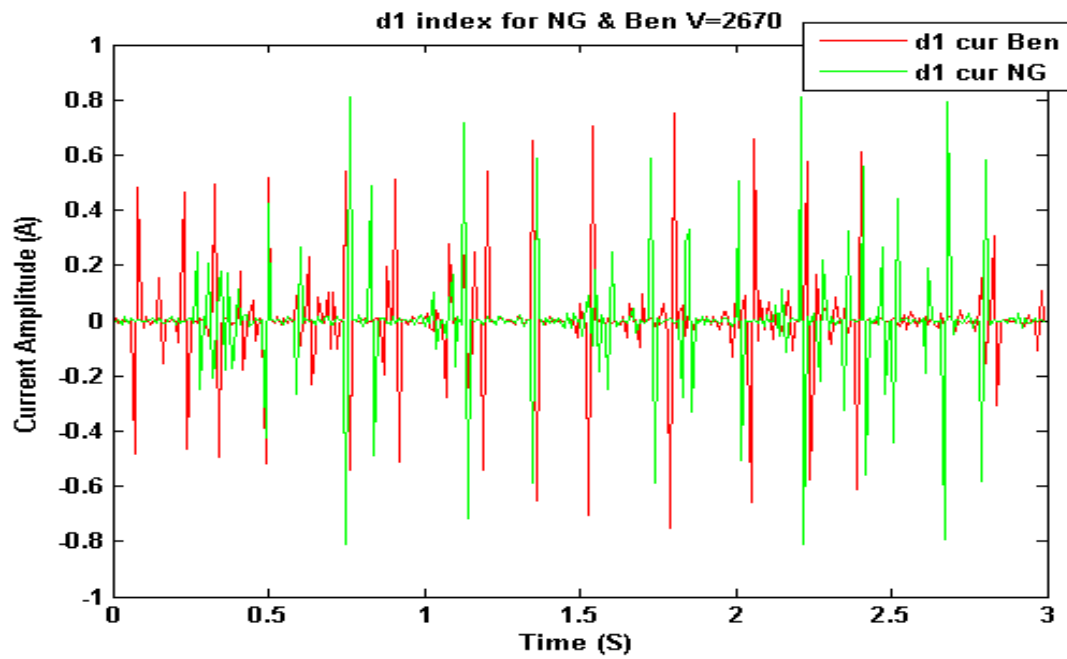


Figure 3.29: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=2670V and H=70%.

The events in Figure 3.29 represent d1 indices for NG and bentonite at V= 2670 V. Various fault current amplitudes for both materials are shown, with the highest changing between 1 and -1 A for the bentonite. As proven in Table 8 the NG reduction rate is higher than the bentonite's one due to the multiple number of high discharges paths observed on the Figure 3.29

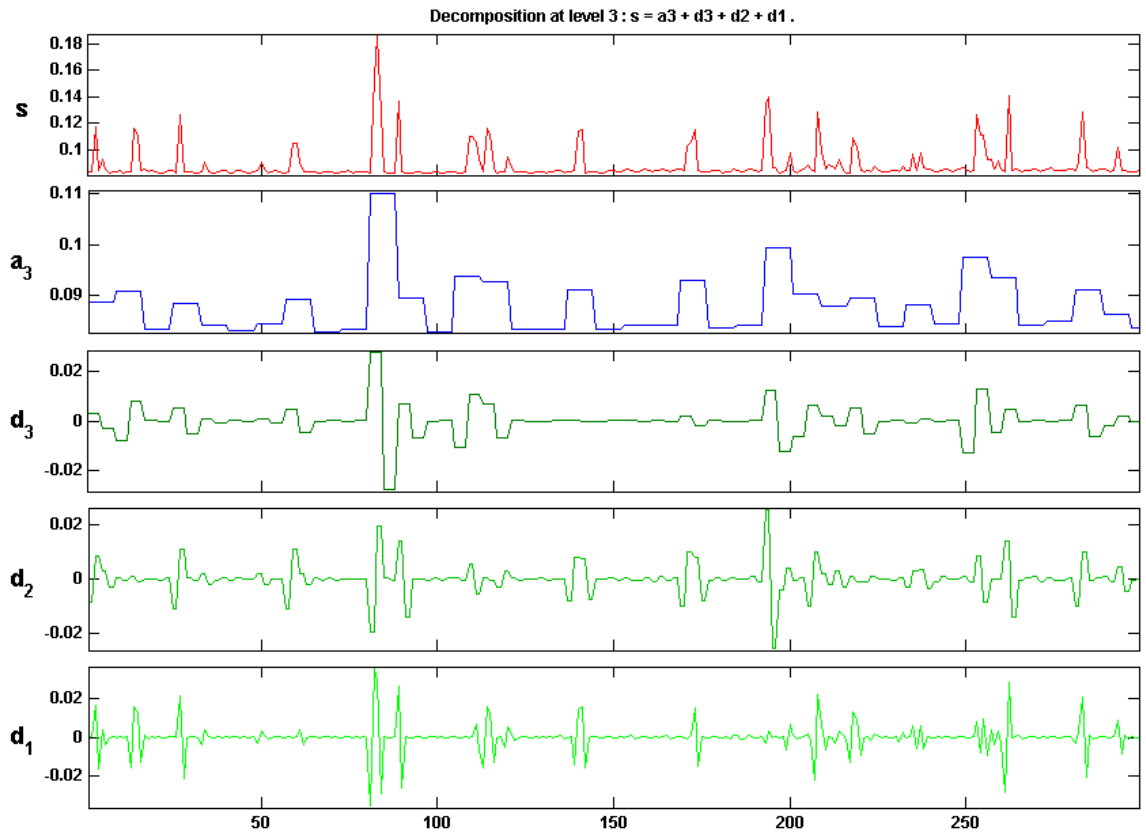


Figure 3.30: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=2900V$ & $H=70\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively.

In Figure 3.30, small fault magnitudes currents are recorded flowing into the soil varying 0.02 A and -0.02 A. The highest is recorded at $t= 2.9$ s for an amplitude of 0.9 A.

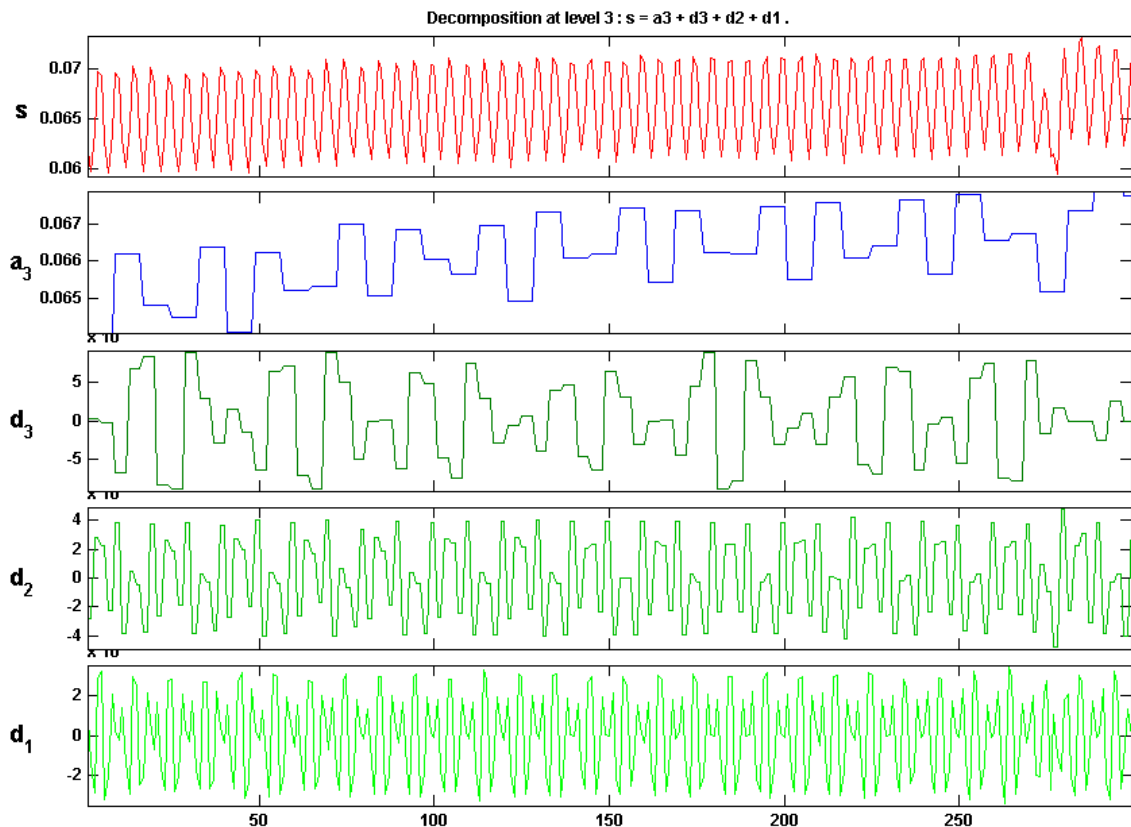


Figure 3.31: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2900V$ & $H=70\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2. and 1. respectively.

No lecture is possible due the noise as the signal is repetitive and the amplitudes changes between 2 A and -2 A.

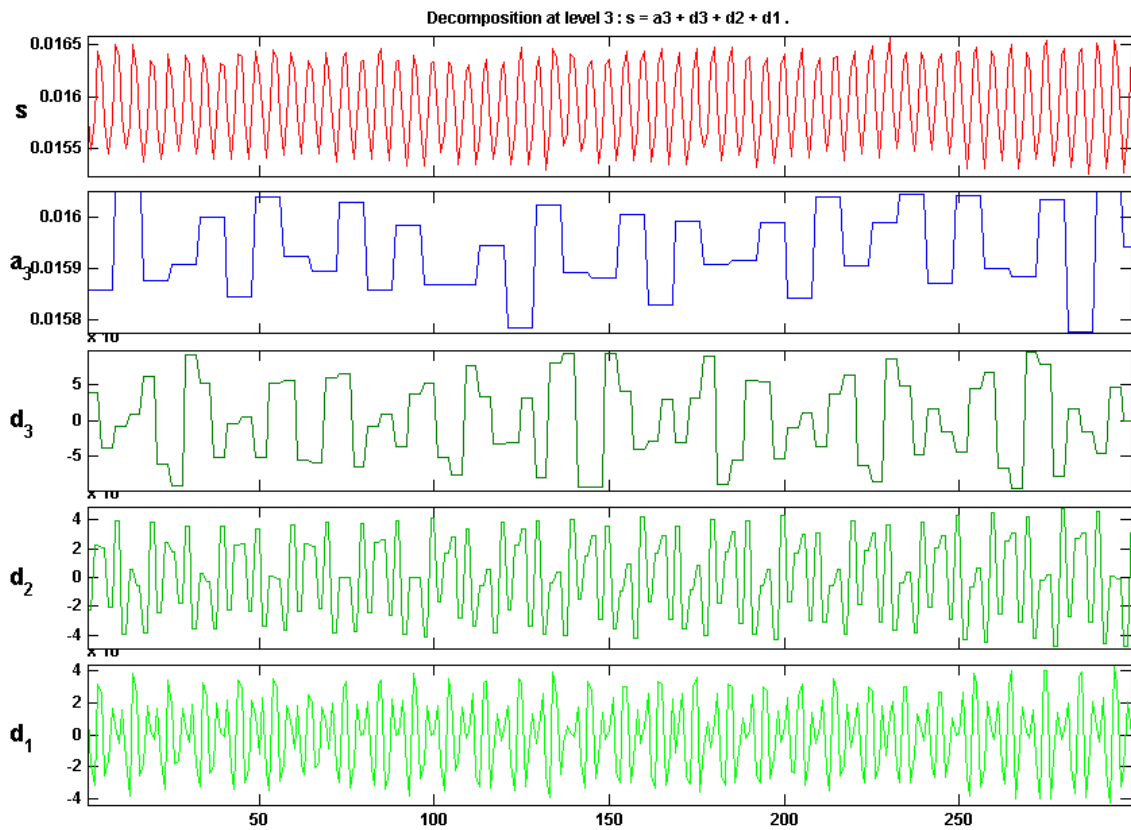


Figure 3.32: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2900V$ & $H=70\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

No lecture is possible due the noise as the signal is repetitive and the amplitudes changes between 4 A and -4 A.

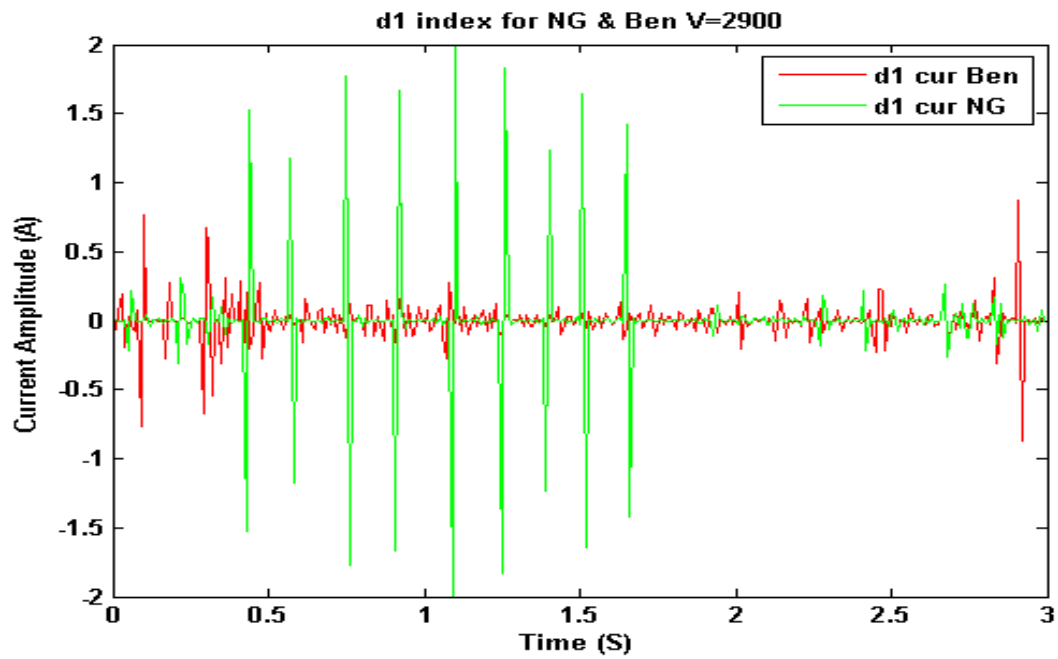


Figure 3.33: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at $V=2900\text{V}$ and $H=70\%$.

The NG present multiple discharge points with different amplitudes and the highest is 2 A at $t=1.1\text{ s}$. Bentonite although it has the earliest dissipation time only reveals a fault at 2.8s changing between of 1 A and -1 A . The NG observed multiple high discharges paths compared to the bentonite.

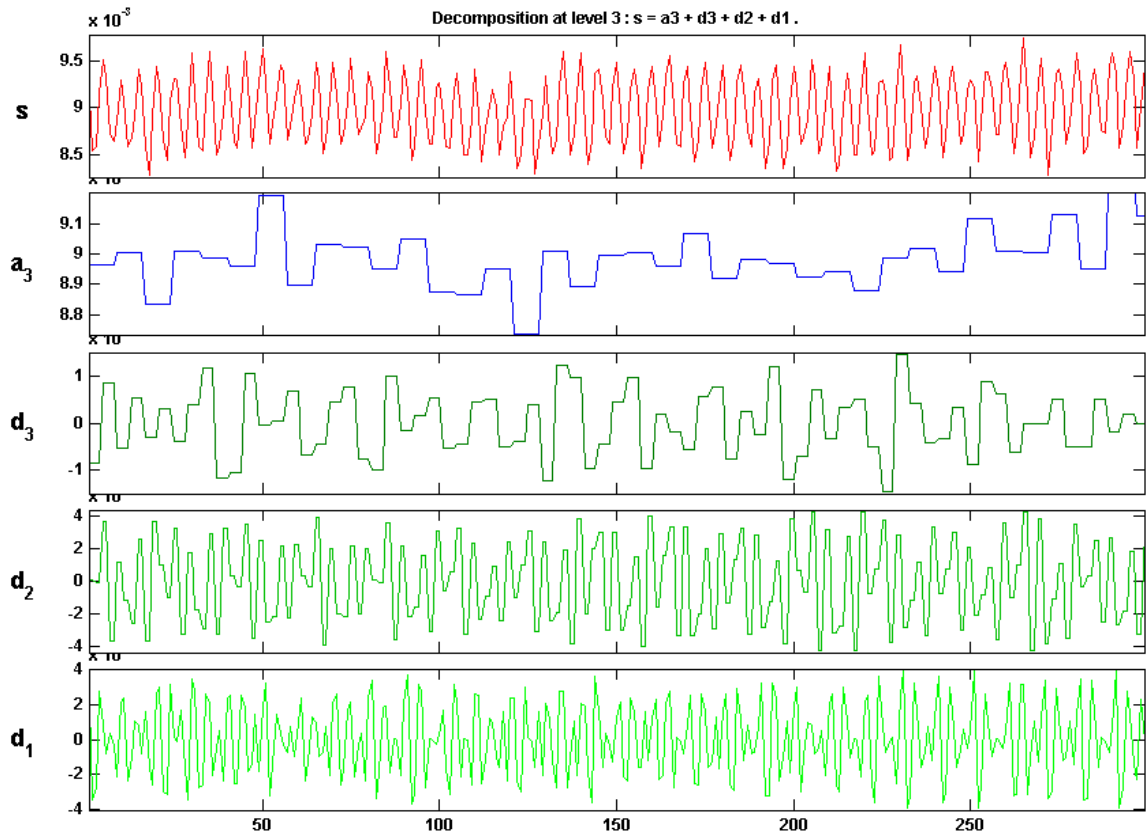


Figure 3.34: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=3760V$ & $H=70\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

The details coefficients for bentonite d1 and d2 present in Figure 3.34 shows multiple discharges over the 4.8s. The discharge magnitude d1 varies between 3A and -3A at $t=1.86s$ to 6A at $t=4.2s$ with the highest peak duration of 0.27s.

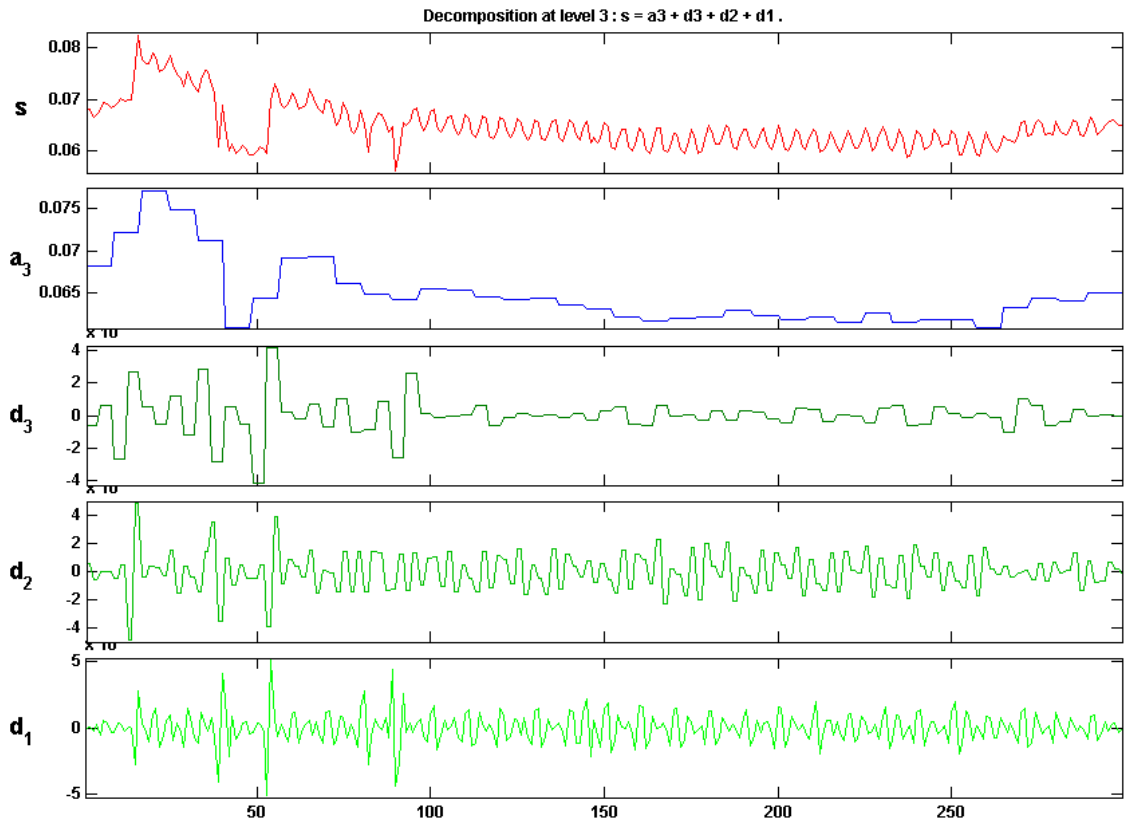


Figure 3.35: DWT based decomposition of the dissipated current signal in the soil for NG at $V=3760V$ & $H=70\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively.

Similar behavior is noticed for natural enhancement material as bentonite in Figure 3.35. Multiple electrical discharges can be seen on d_1 and d_2 in the range of 5A and -5 A at $t=2.55s$ from highest to the lowest with 0.24s highest peak duration.

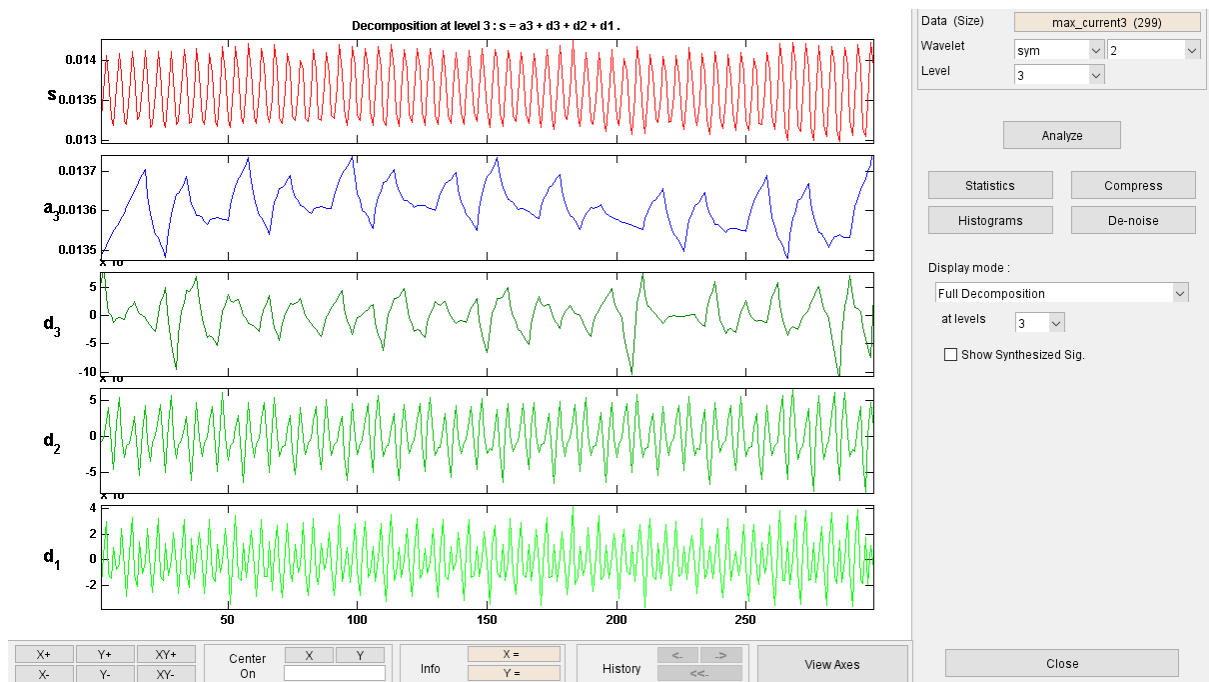


Figure 3.36: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=3760V$ & $H=70\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively. No lecture is possible due the noise

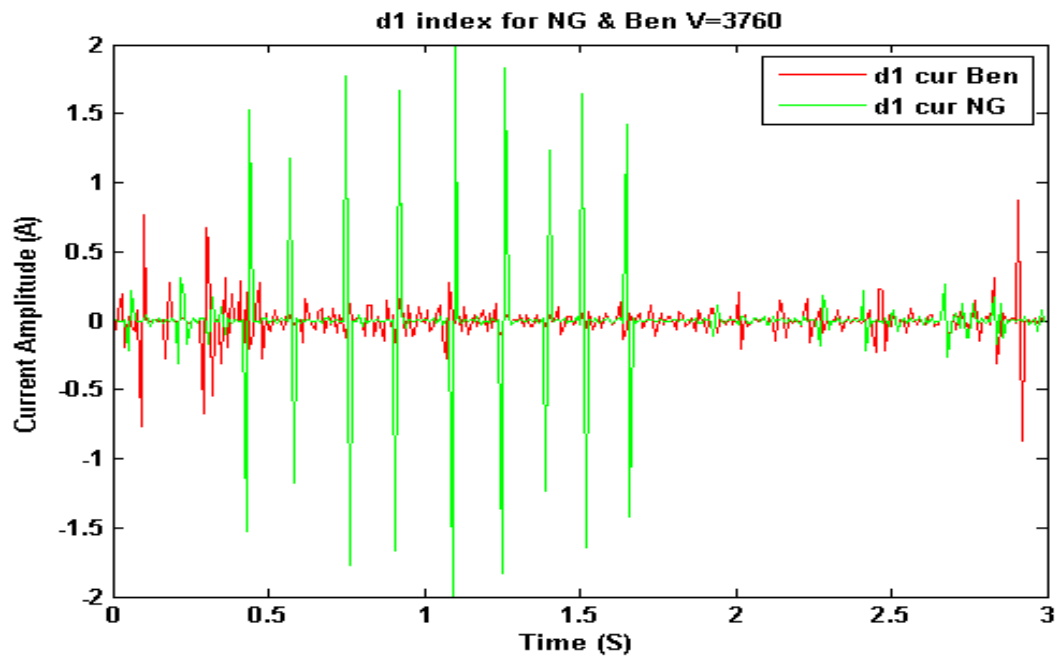


Figure 3.37: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=3760V and H=70%.

Figure 3.37 presents the first decomposition level for both natural enhancement material and the bentonite. Both registered an increase in the dissipation path as the humidity increased. As shown in Figure 3.34 and in Figure 3.35, it is noticeable that the number of discharge signals has increased. Based on these readings, the findings show that the bentonite performance depends on the humidity level. These findings support the conclusion in Table 8.

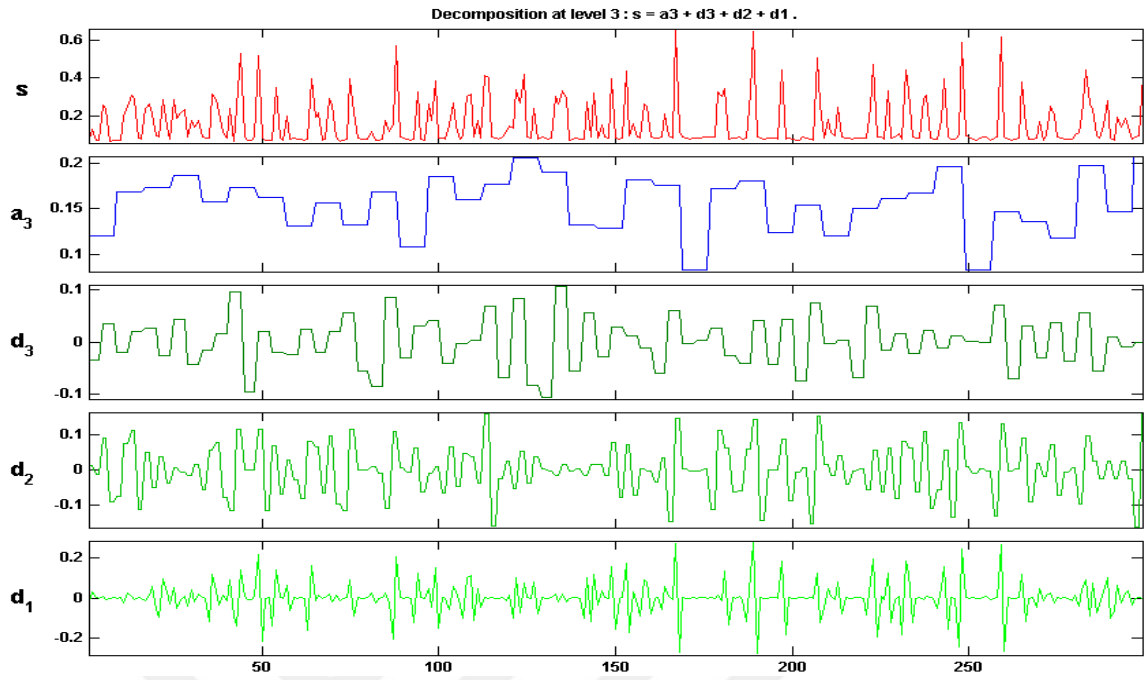


Figure 3.38: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=2050V$ & $H=72\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively.

Figure 3.38 shows discharges with amplitude varying between 0.2 A to 0.6 A.

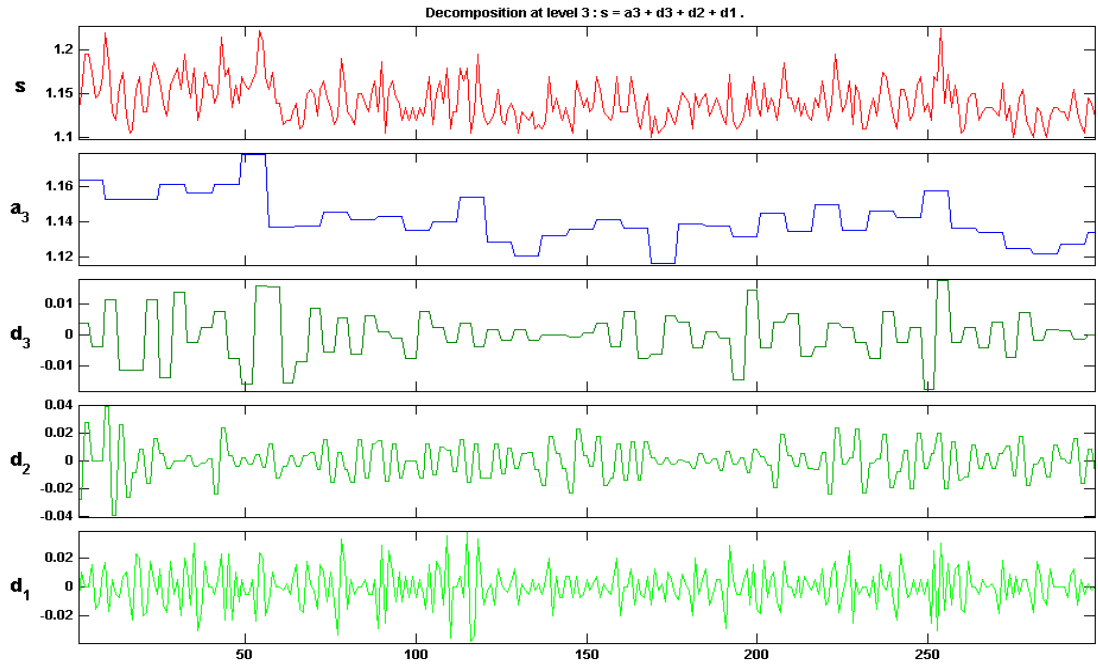


Figure 3.39: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2050V$ & $H=72\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively.

Very weak discharges are observed on Figure 3.39 compared to others voltage levels compared to the other voltage levels.

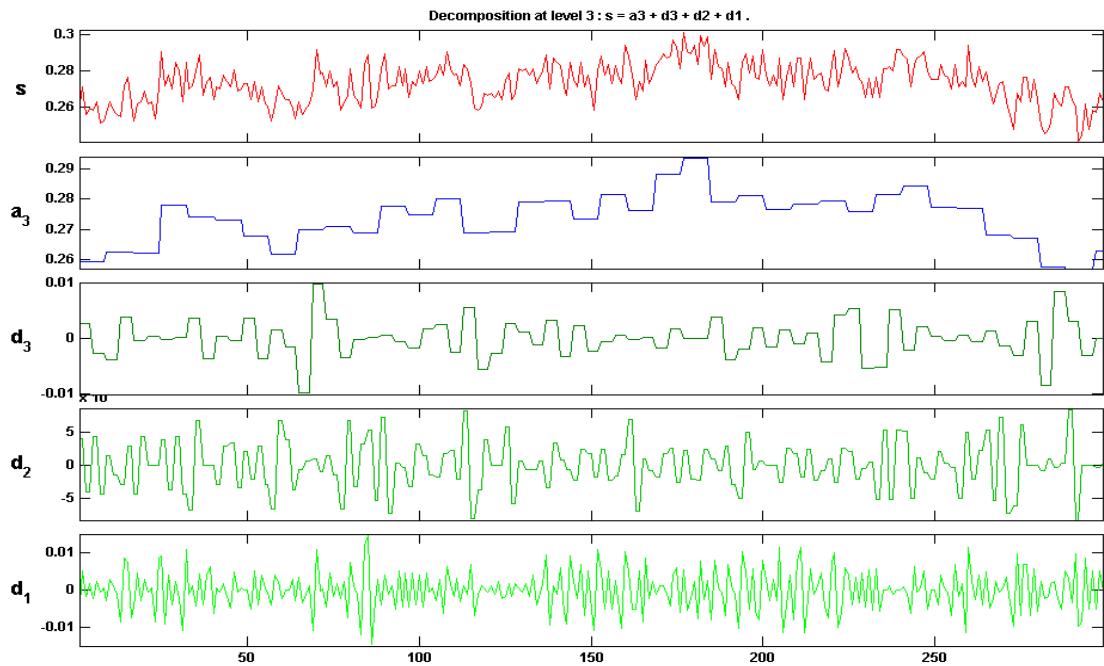


Figure 3.40: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2050V$ & $H=72\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

No lecture is possible due the noise

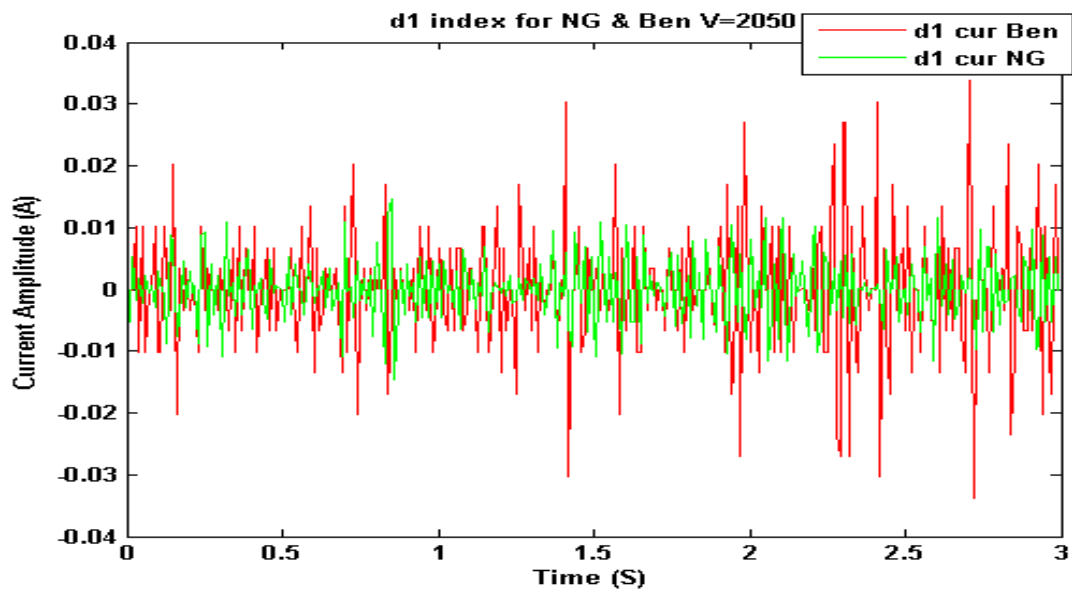


Figure 3.41: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=2050V and H=72%.

Although the signals in Figure 3.41 are not clearly visible, we can defer from it the bentonite signal amplitude changes between 0.035 A and -0.035 A. The NG signal is too small for reading.

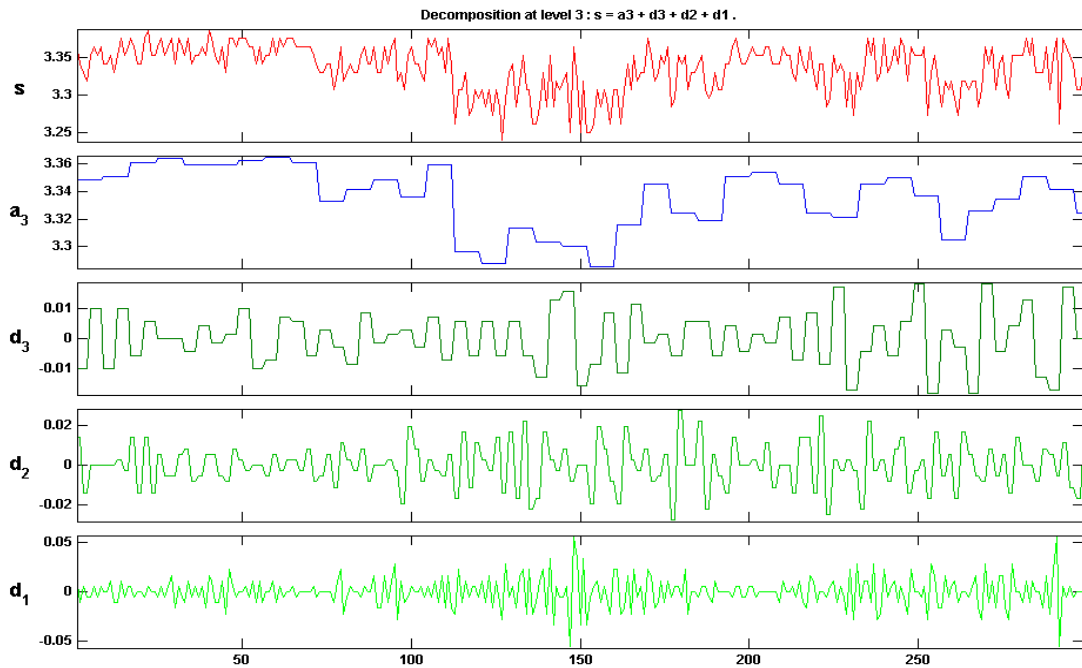


Figure 3.42: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=2670V$ & $H=72\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. The first quadran of the d_1 indice is nearly zero. The second records some oxcillations with an amplitude of 0.1 A and slowly die out.

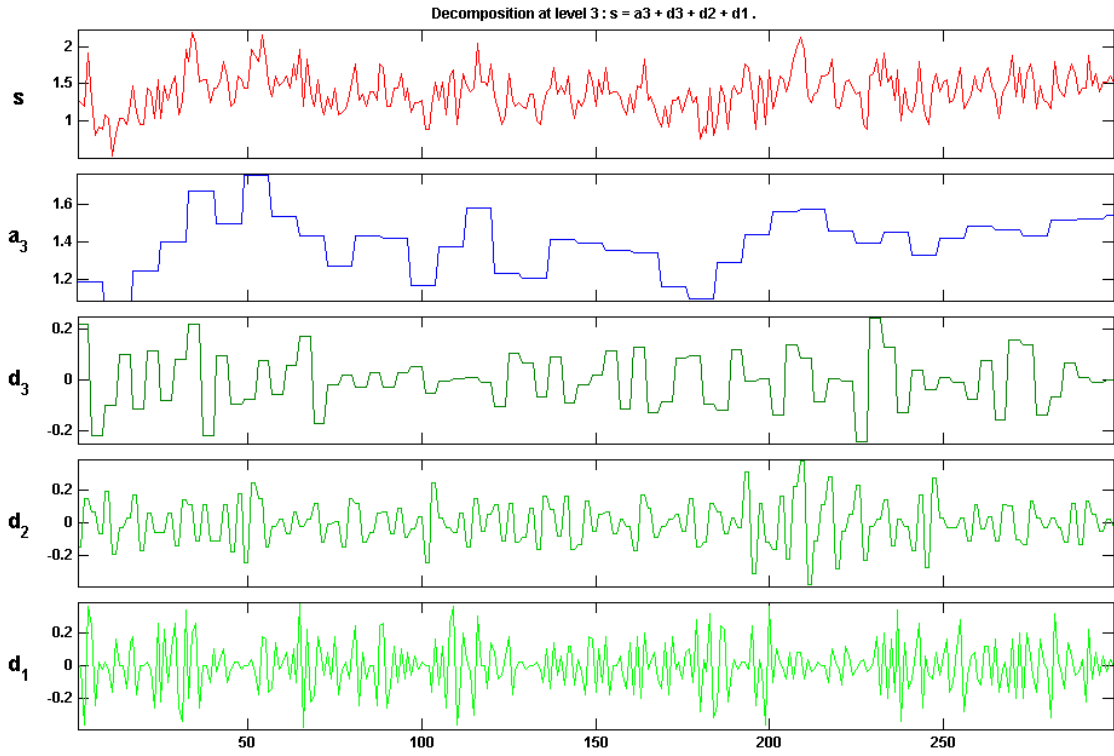


Figure 3.43: DWT based decomposition of the dissipated current signal in the soil for NG at V=2670V & H=72%. (s) Original current signal (a₃) approximation coefficient of 3. Decomposition level (d₃), (d₂) & (d₁) are detail coefficients of level 3, 2, and 1, respectively.

Earliest peak happens at $t=0.02$ s with the high of 0.4 A. The rest of the signal witnessed various peaks with different amplitudes.

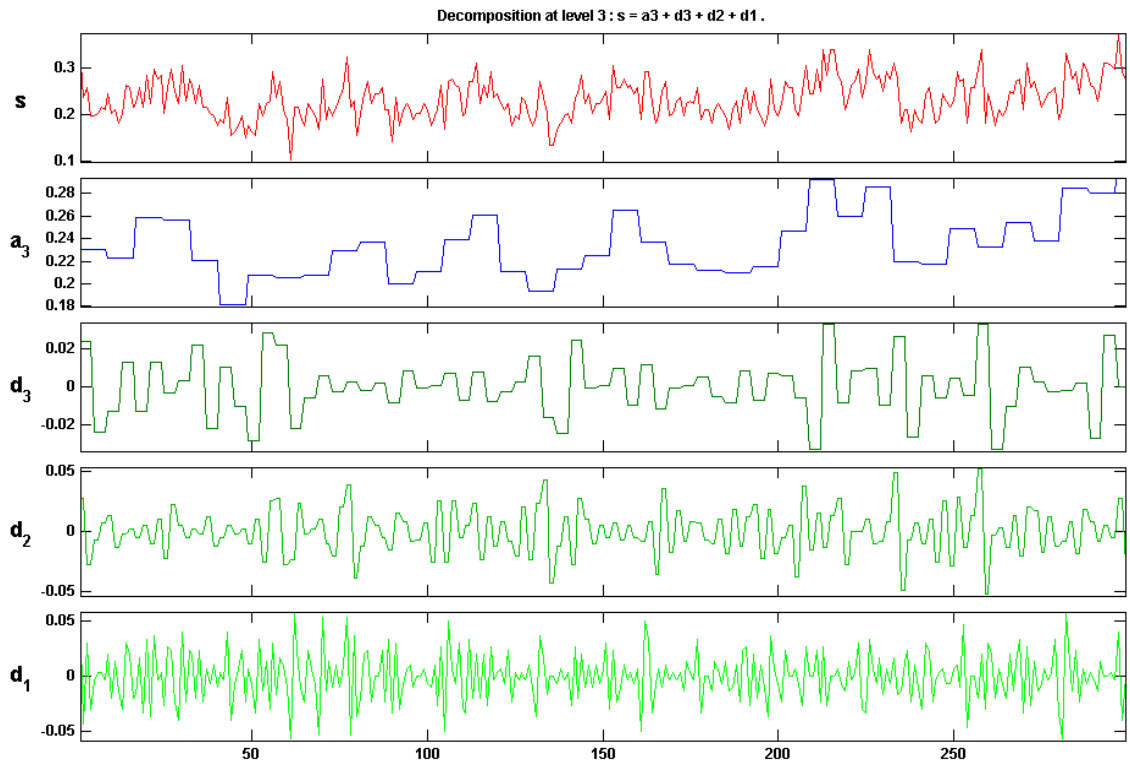


Figure 3.44: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2670V$ & $H=72\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

No lecture is possible due the noise.

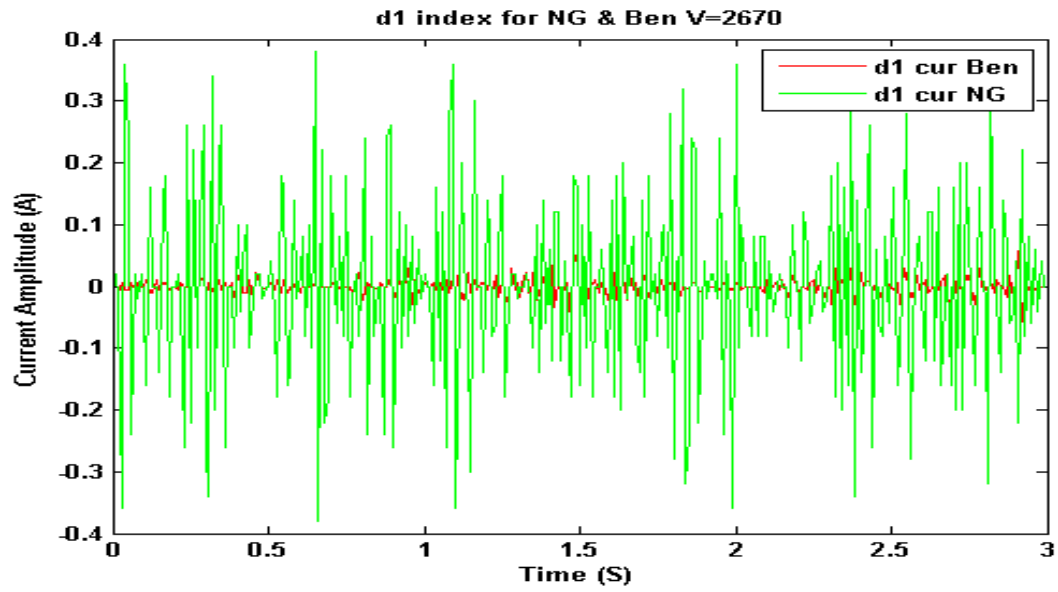


Figure 3.45: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=2670V and H=72%.

The NG shows many discharges point with the first an the highest at $t=0.005$ s for and amplitude varying between 0.4 A and -0.4 A. The signal for the bentonite was too small to be seen in the Figure 3.45. As in Table 9, the NG shows a better performance due to multiple discharges paths.

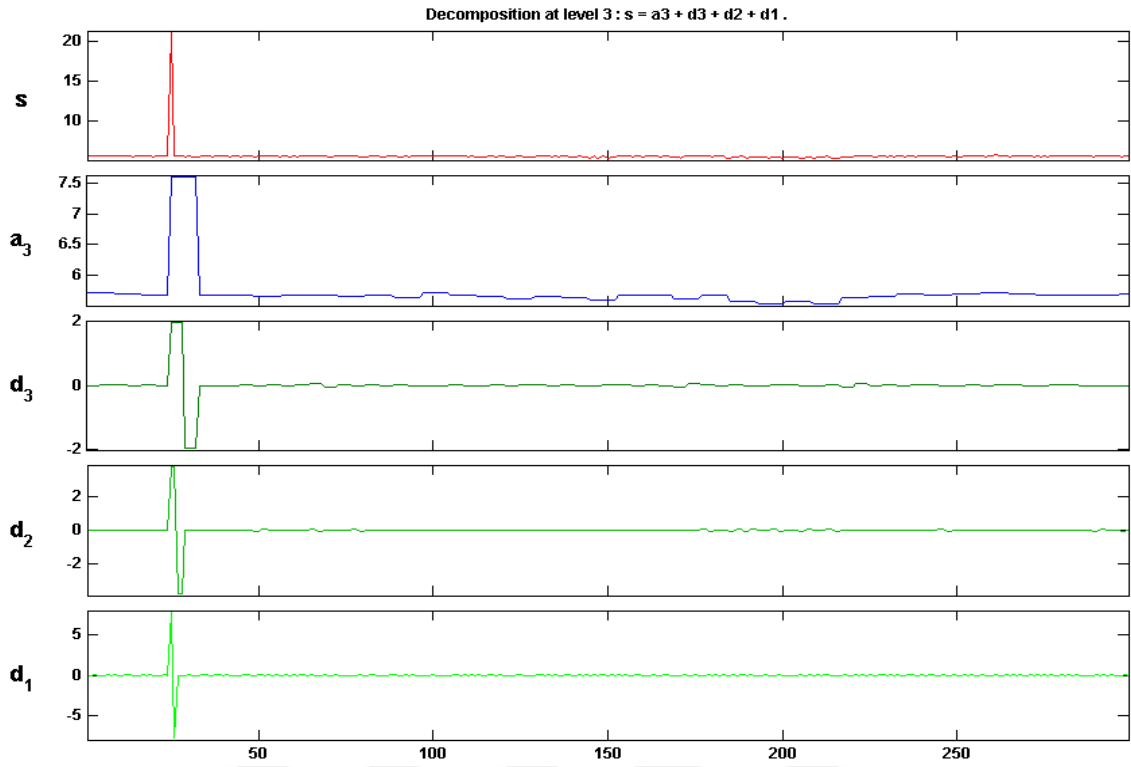


Figure 3.46: DWT based decomposition of the dissipated current signal in the soil for bentonite at V=2900V & H=72%. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

The event corresponding to d1 index in Figure 3.46 shows one discharge with an amplitude changing between 6 A and -6 A and the rest of the signal dies out.

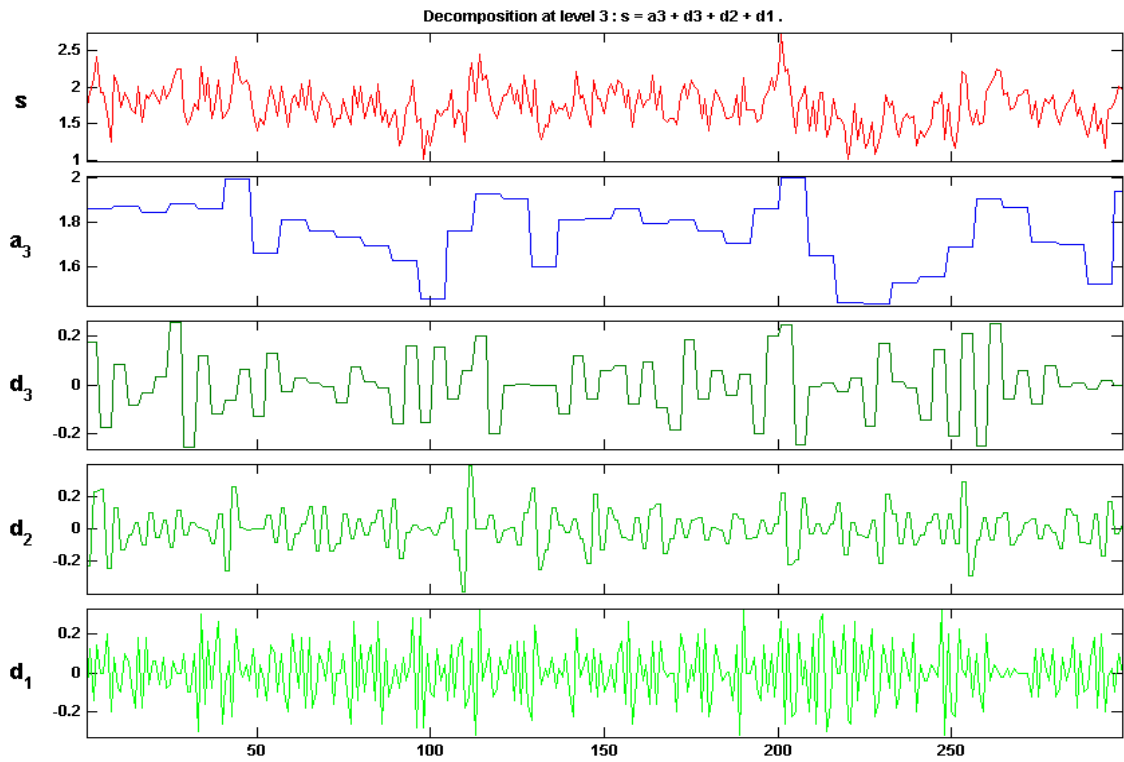


Figure 3.47: DWT based decomposition of the dissipated current signal in the soil for NG at V=2900V & H=72%. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

No lecture is possible due the noise.

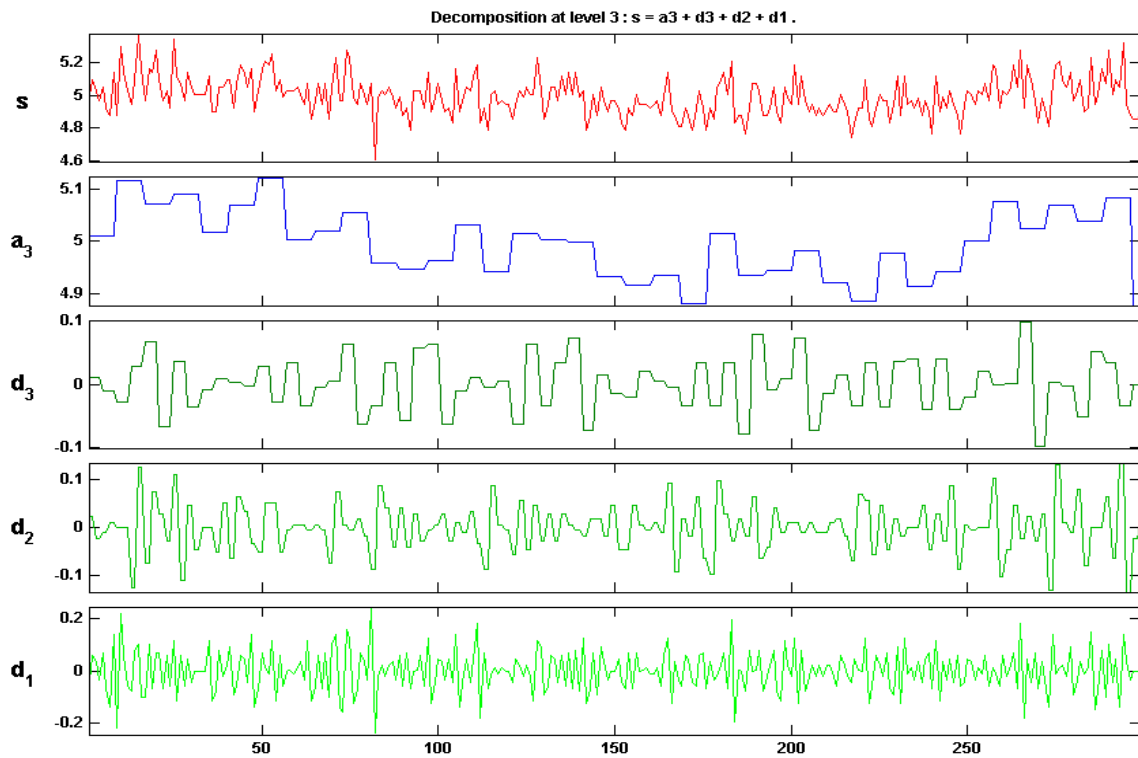


Figure 3.48: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2900V$ & $H=72\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively.

No lecture is possible due the noise.

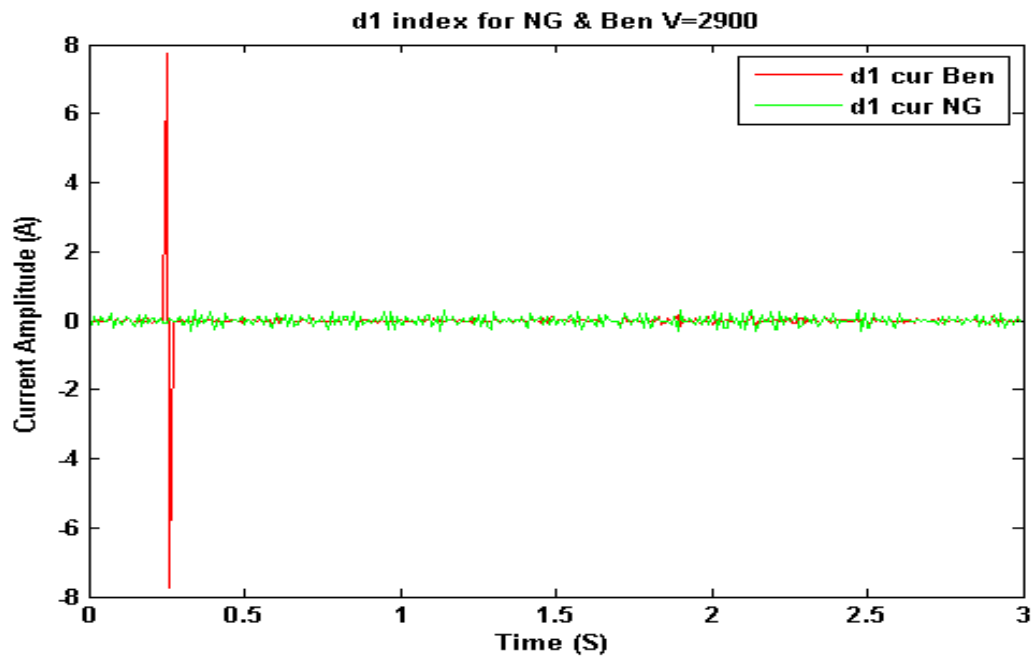


Figure 4.49: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=2900V and H=72%.

As we could not get a clear reading in Figure 4.47 and Figure 4.49 only shows the dissipated current for the bentonite. The dissipation point is at $t=0.25$ for an amplitude of 8 A.

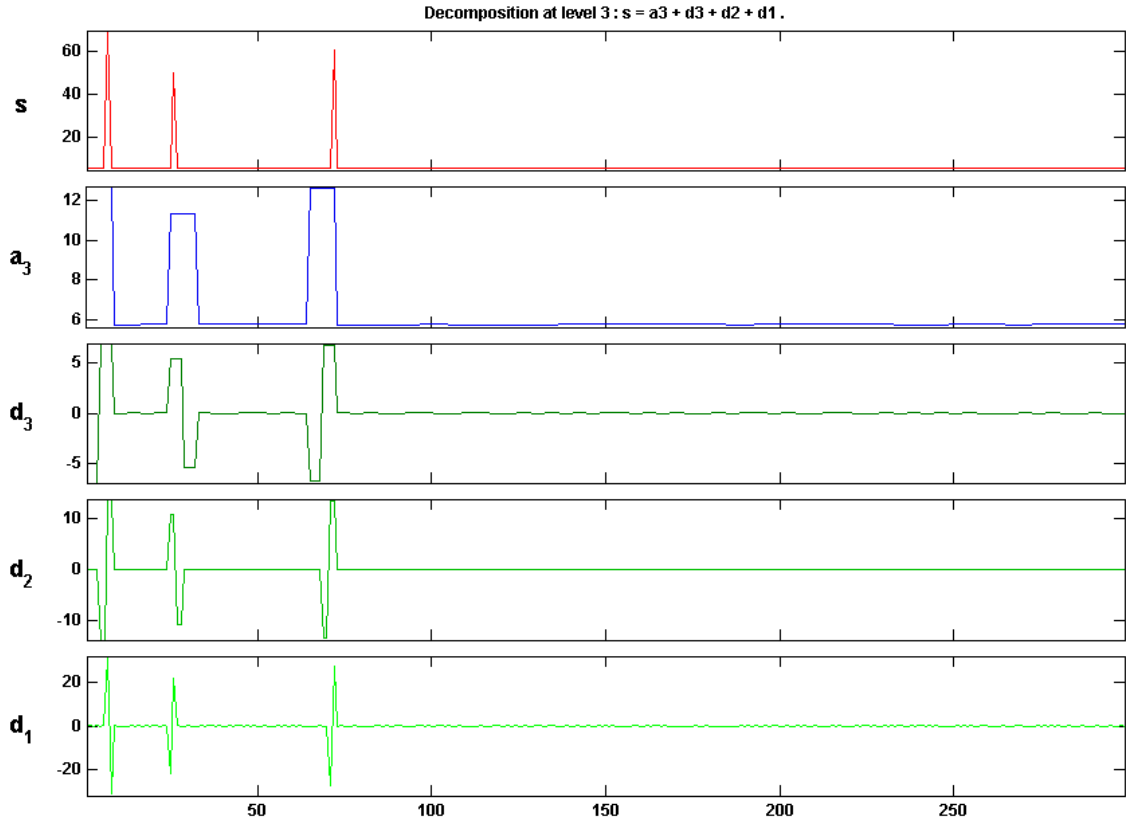


Figure 4.50: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=3760V$ & $H=72\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively.

The analysis of Figure 4.50 proves three main events have occurred during the experiment time with 2 peaks recorded at $t=0.1$ s, 0.25 s and 0.65 s. The magnitudes of the d_1 change from 20 A and -20 A for the first event and from 25 A and 25 A from the lowest to the highest. Duration for the highest is 0.24 s.

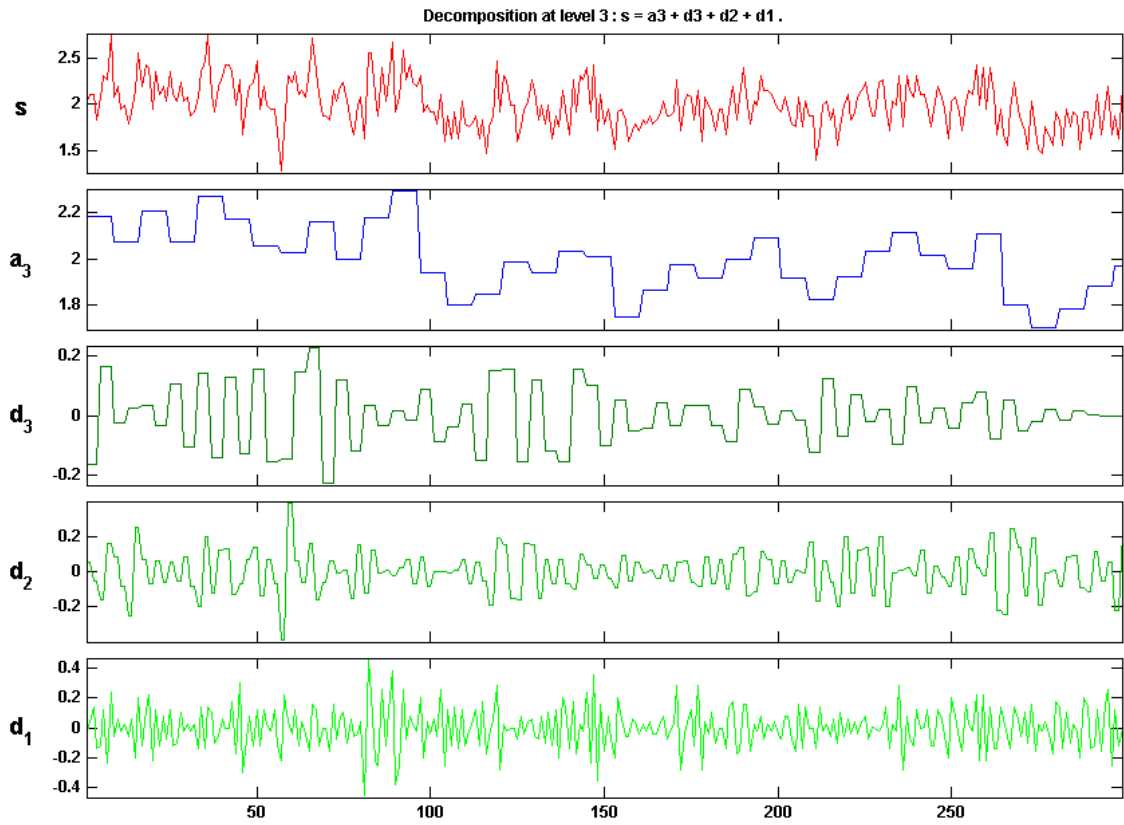


Figure 4.51: DWT based decomposition of the dissipated current signal in the soil for NG at V=3760V & H=72%. (s) Original current signal (a₃) approximation coefficient of 3. Decomposition level (d₃), (d₂) & (d₁) are detail coefficients of level 3, 2, and 1, respectively.

The DWT decomposition coefficients d₁, d₂, and d₃ in Figure 4.51 don't reveal much as the signal recorded has too much noise. Though d₁ changes between 0.25 A and -0.25 A.

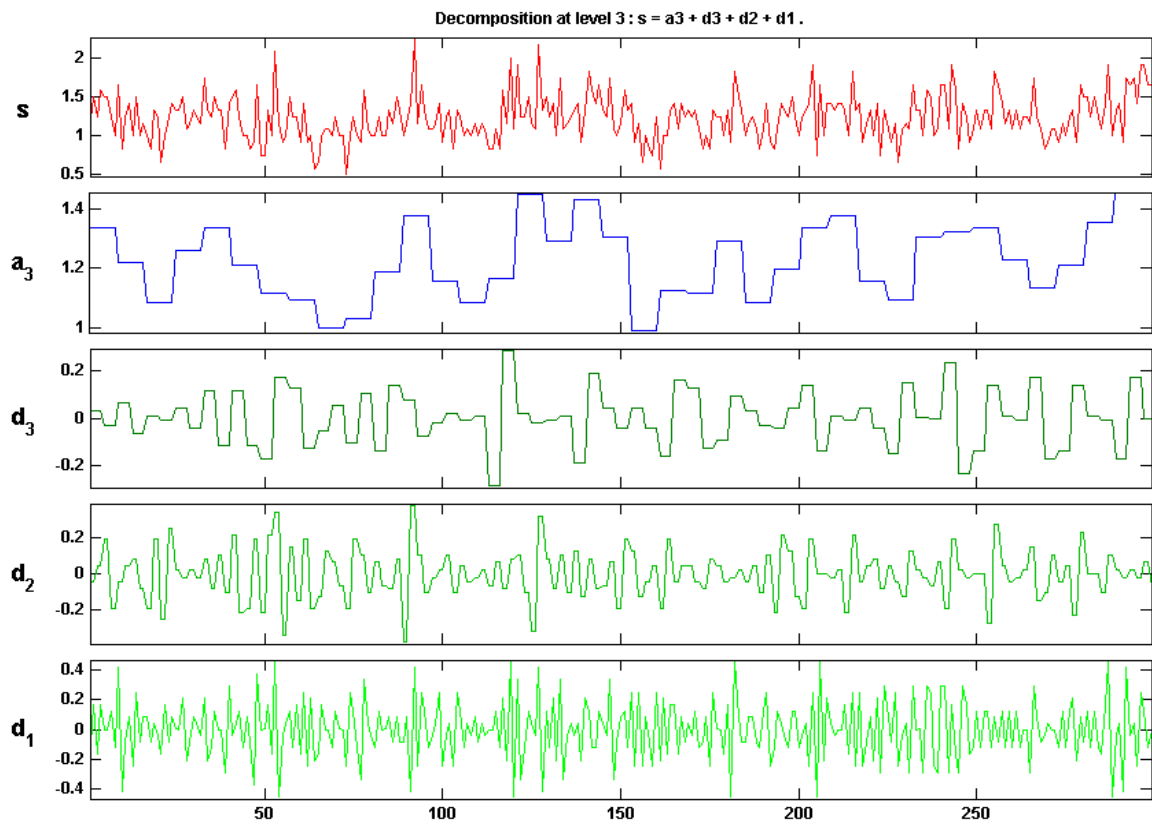


Figure 4.52: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=3760V$ & $H=72\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

No lecture is possible due the noise.

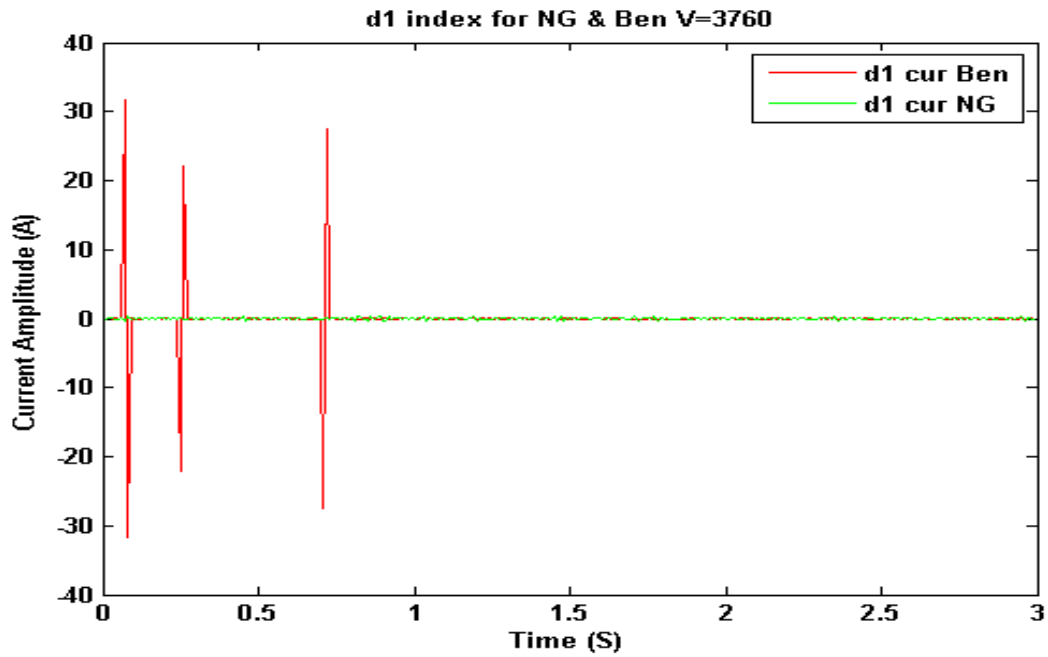


Figure 4.53: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=3760V and H=72%.

The events happened in NG can't be seen because their amplitudes are too small. As stated in Figure 4.53, NG fault current changes between 0.25 A and -0.25A. But the bentonite, 3 main events of different amplitudes are recorded. The first one happening at $t=0.1$ with an amplitude 30 A followed by another one at $t=0.25$ s for an amplitude of 22.4 A. The last discharge happened at 0.65s with 28A current dissipated in the ground. The performance of bentonite is much higher as in Table 9.

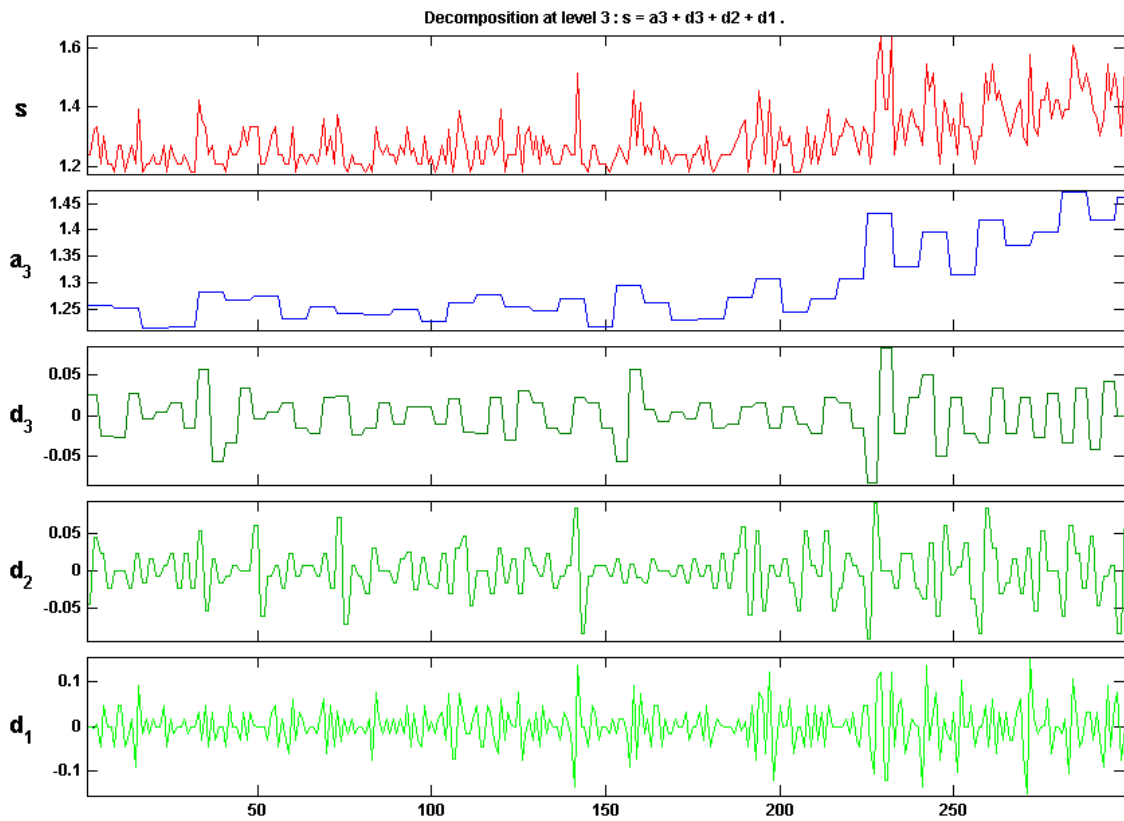


Figure 4.54: DWT based decomposition of the dissipated current signal in the soil for bentonite at V=2050V & H=75%. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

Weak response is recorded for the bentonite fault current. The highest amplitudes vary between 0.1 A and 0.16 A. Most the signal is nearly zero besides the small discharge points.

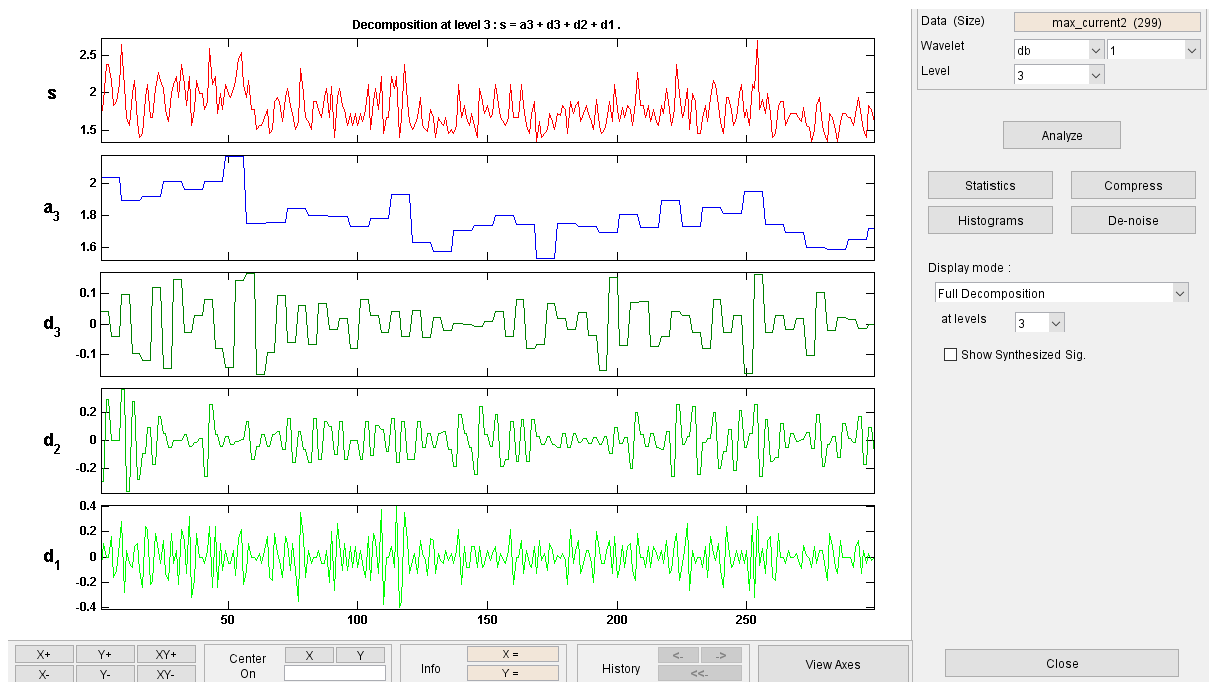


Figure 4.55: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2050V$ & $H=75\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively. The amplitudes of the signal are much higher compared to Figure 4.54. The NG peak changes between 0.2 A and 0.4 A.

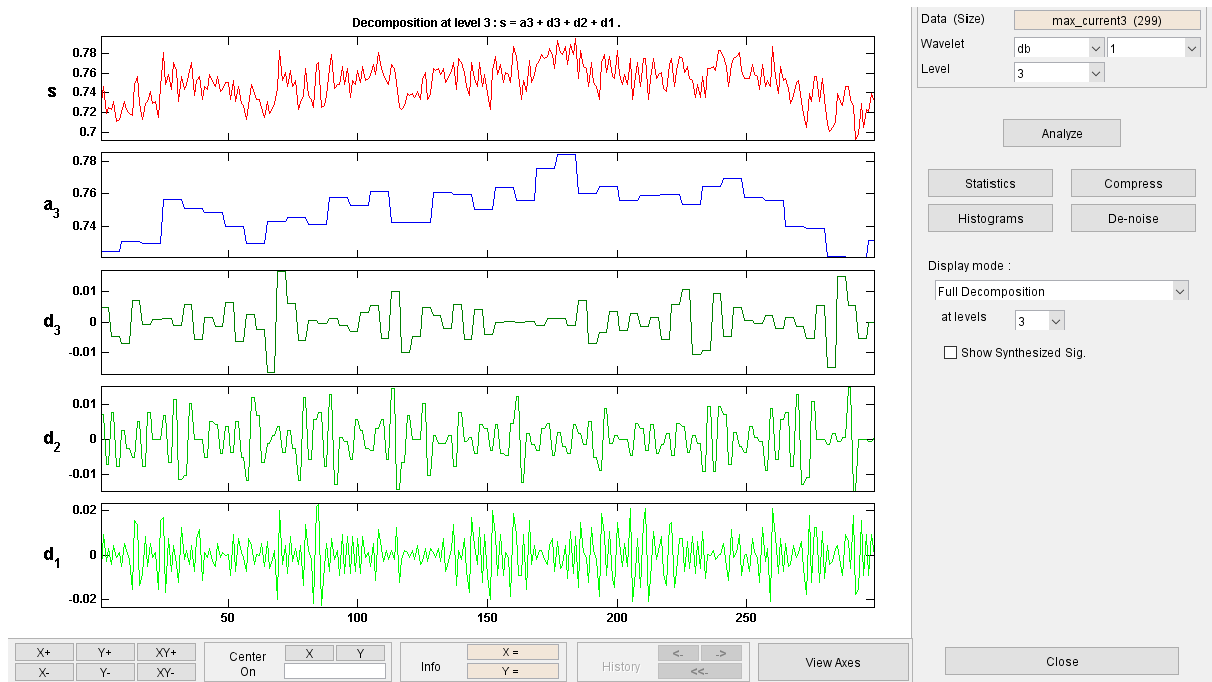


Figure 4.56: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2050$ V & $H=75\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively. The signal response is too weak and is considered to be zero.

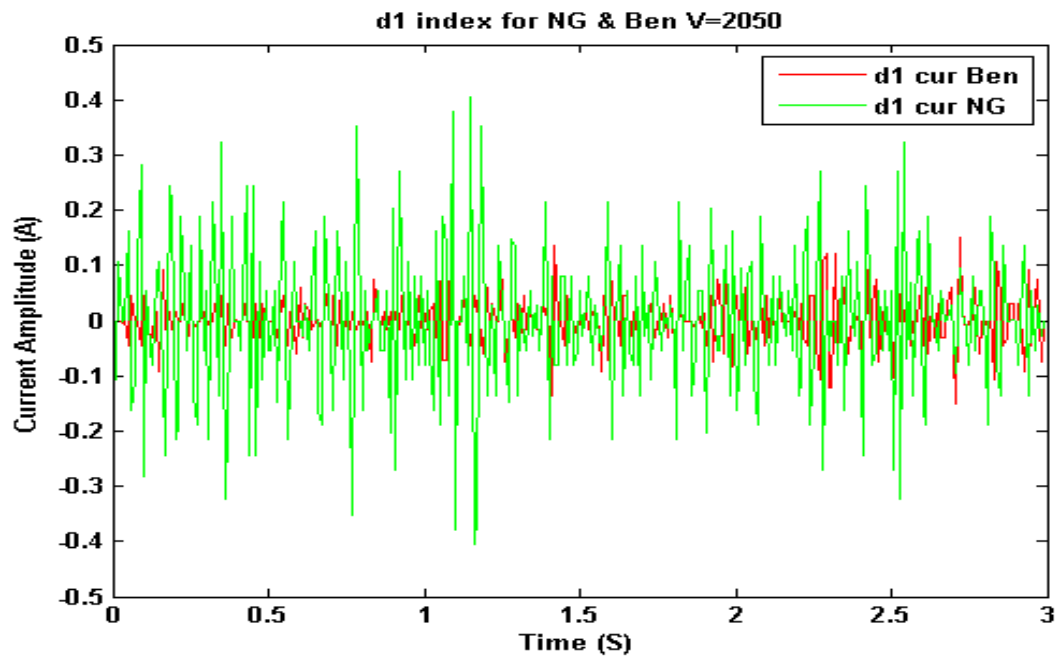


Figure 4.57: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=2050V and H=75%.

The NG shows many discharges point with the first and earliest highest discharge at $t=0.005s$ for and amplitude varying between 0.4 A and -0.4 A. The bentonite fault current is seen to be small. As in Table 10, NG performs much better.

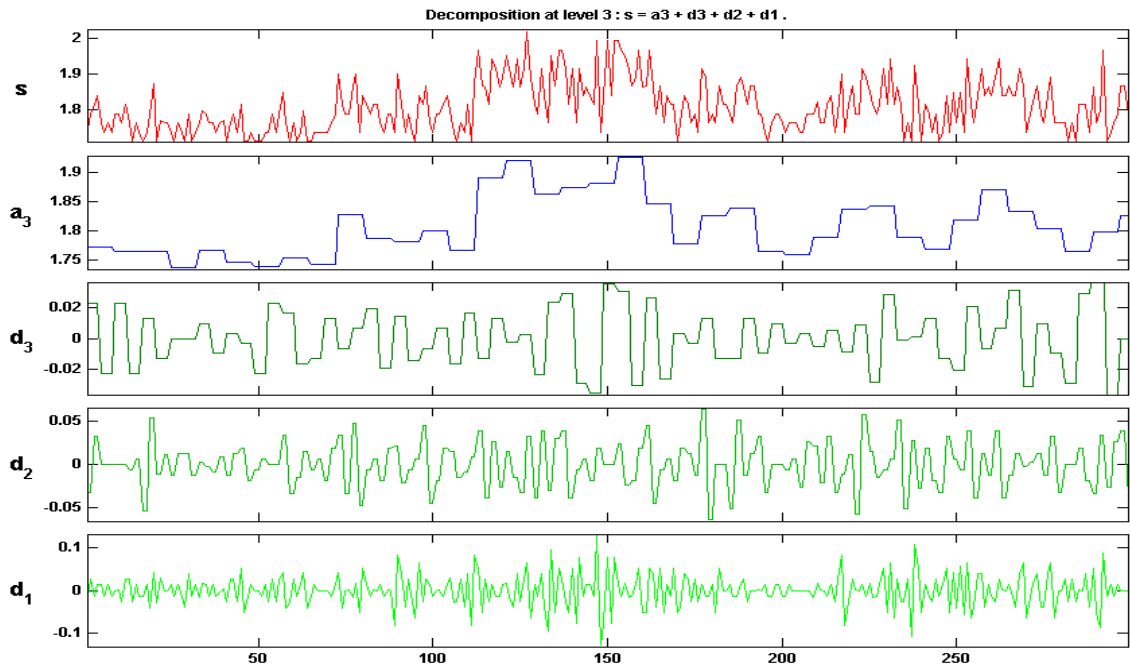


Figure 4.58: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=2670V$ & $H=75\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. The event corresponding to the detail coefficient d_1 and d_2 are illustrated in Figure 4.58 for the bentonite. The values of the current flow are nearly zero with d_1 changing between $0.1A$ and $-0.1A$. The fault current is much higher than the Figure 4.54

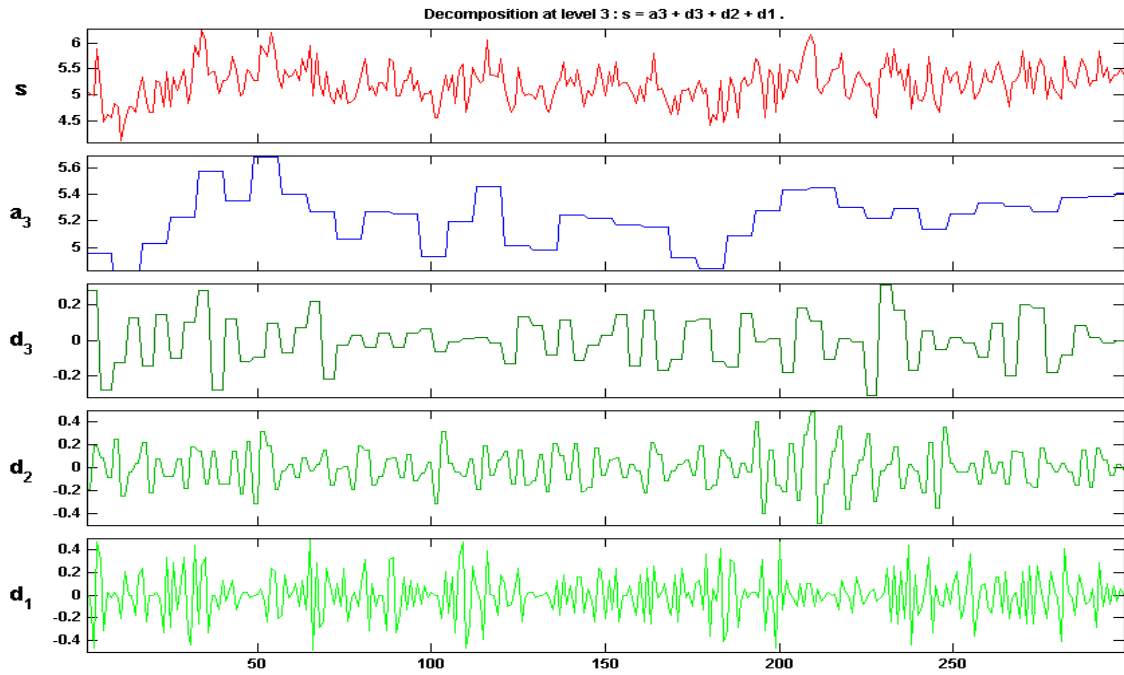


Figure 4.59: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2670V$ & $H=75\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. The event corresponding to the detail coefficient d_1 and d_2 are illustrated in Figure 4.59 for natural enhancement material. The values of the current flow are nearly zero with d_1 changing between $0.5A$ and $-0.5A$.

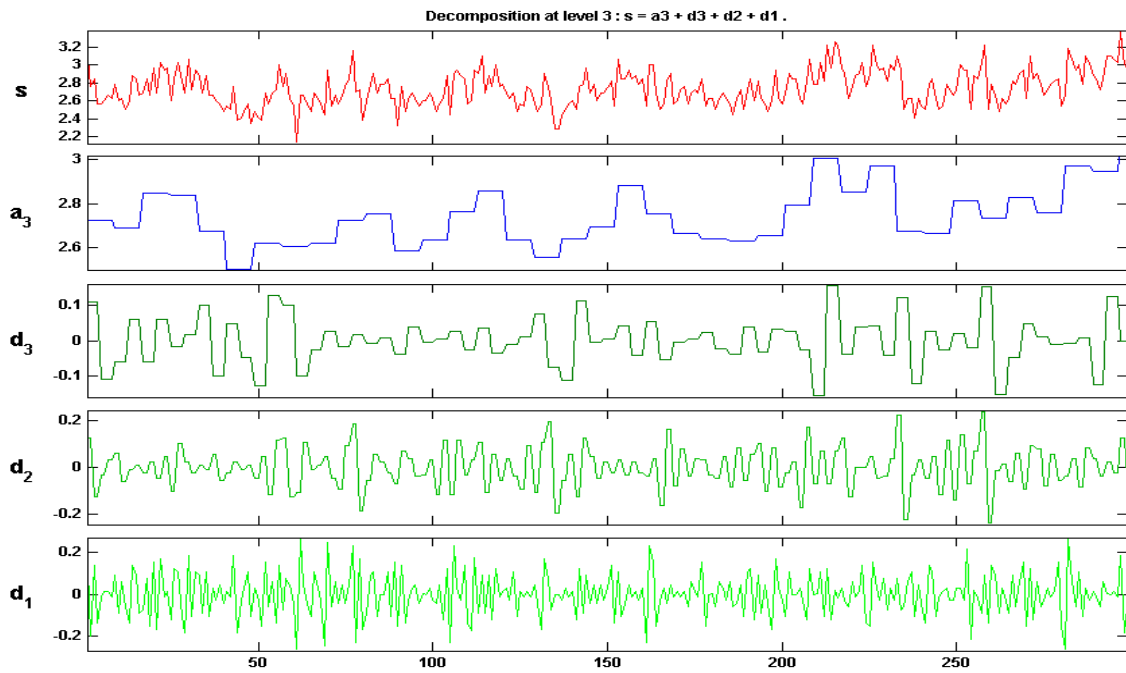


Figure 4.60: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2670$ V & $H=75\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. No lecture is possible due the noise.

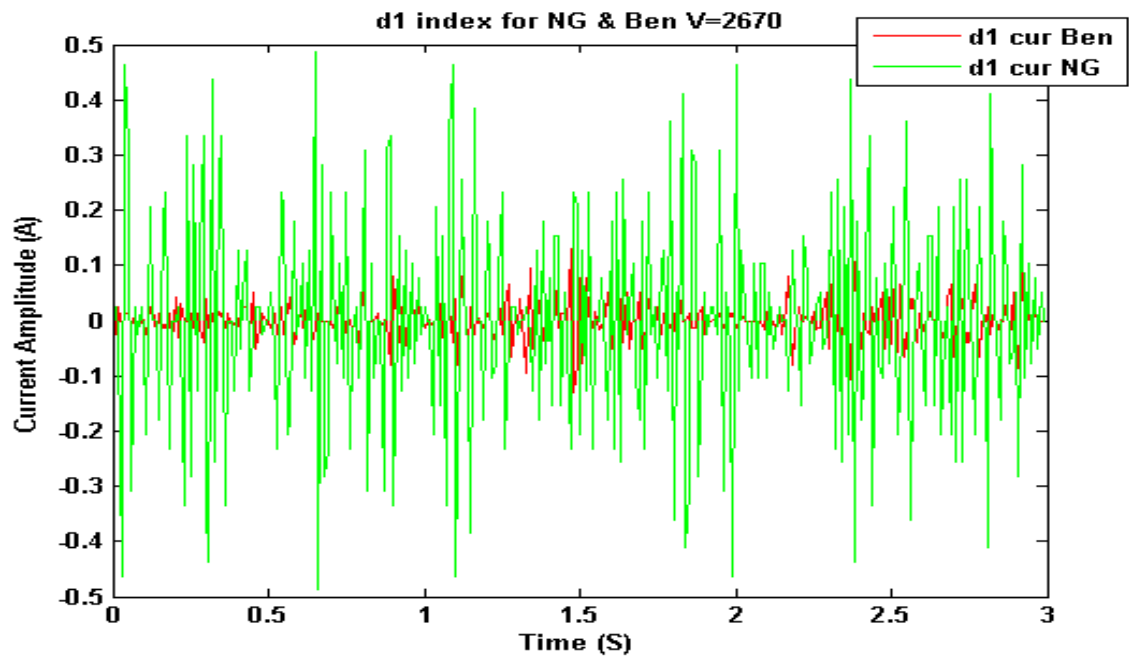


Figure 4.61: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=2670 V and H=75%.

While the bentonite d1 indice changes between 0.1 A and -0.1 A, the NG'd1 shows many discharges point with the first and the highest at $t=0.005$ s for and amplitude varying between 0.5 A and -0.5 A. The same conclusion was reached in Table 10.

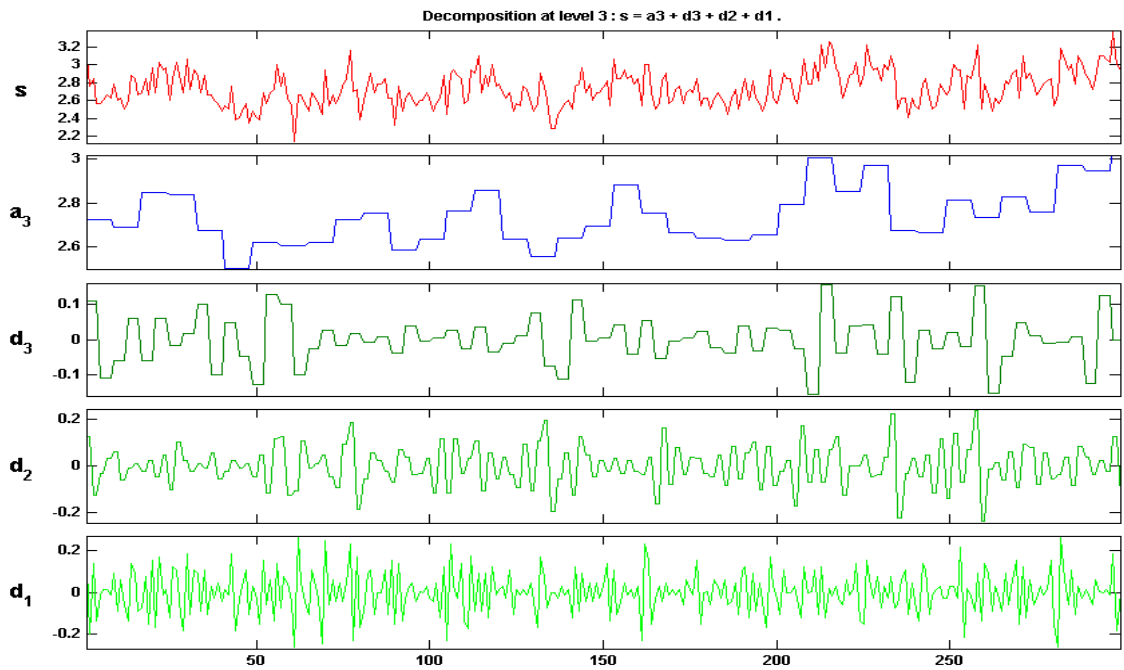


Figure 4.62: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=2900V$ & $H=75\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. The event corresponding to the detail coefficient d_1 and d_2 are illustrated in Figure 4.62 for the bentonite. In this case the values of the current flow are nearly zero with d_1 changing between 0.2A and -0.2A.

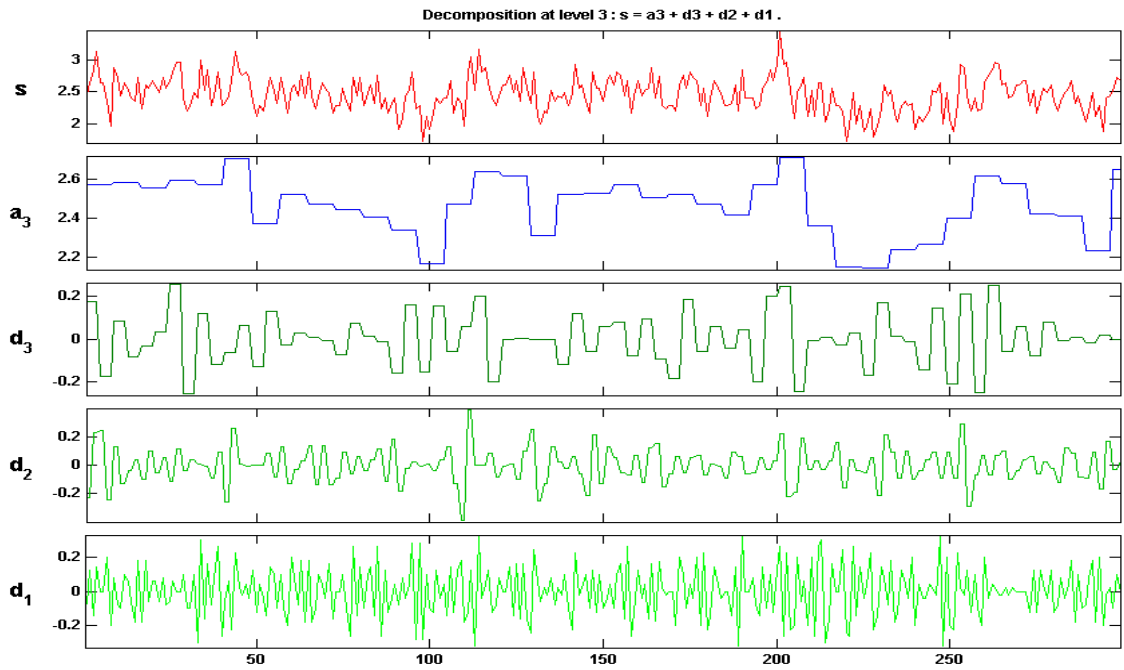


Figure 4.63: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2900V$ & $H=75\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. The event corresponding to the detail coefficient d_1 and d_2 are illustrated in Figure 4.63 for natural enhancement material. The values of the current flow are small with d_1 changing between $0.3A$ and $-0.3A$.

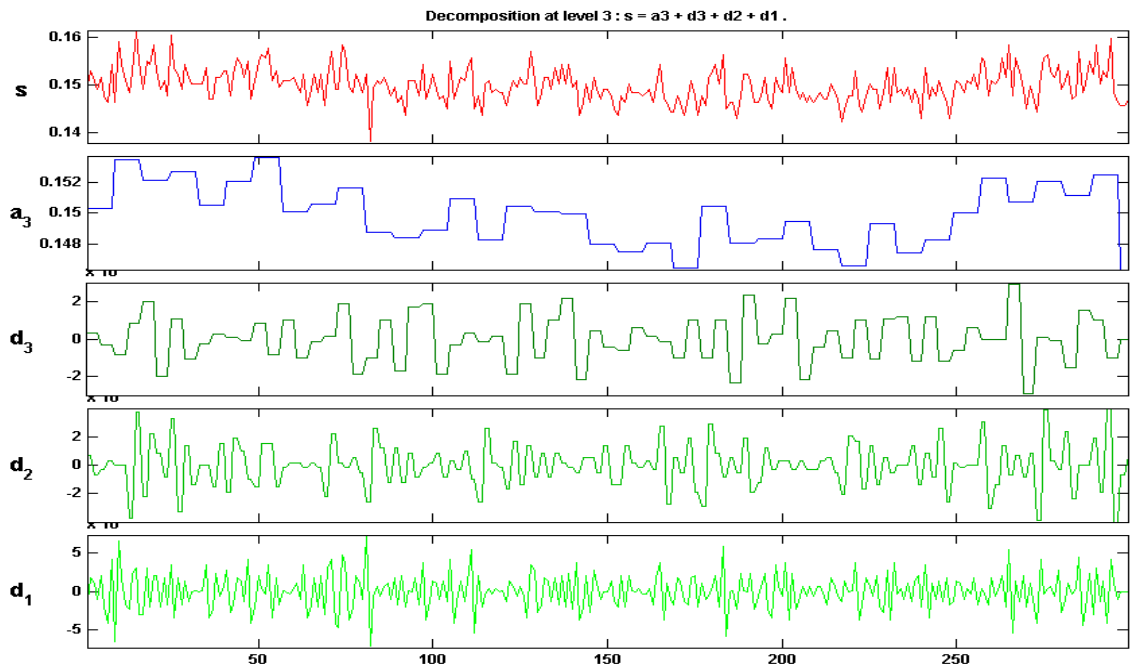


Figure 3.64: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2900$ V & $H=75\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. The change in d_1 indice for the normal soil is 5 A. It is higher than bentonite and NG.

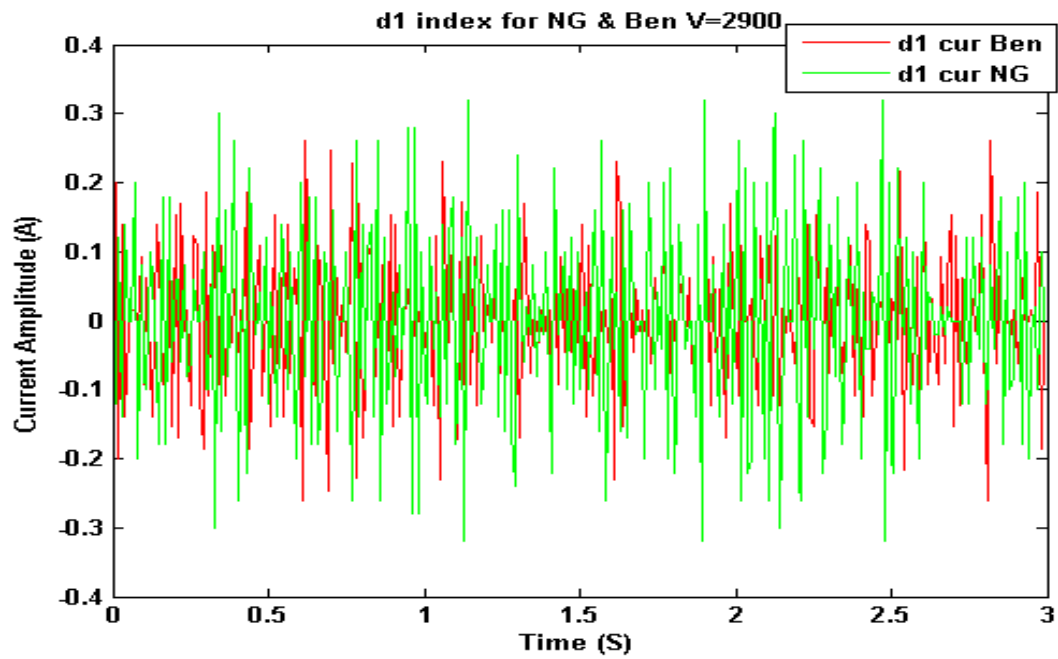


Figure 3.65: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at $V=2900$ V and $H=75\%$.

Both signals show many discharges point with the first an the highest at $t=2.5$ s for the NG and amplitude varying between 0.4 A and -0.4 A. Table 10 corrolates the similar result as the NG as higher dissipation paths.

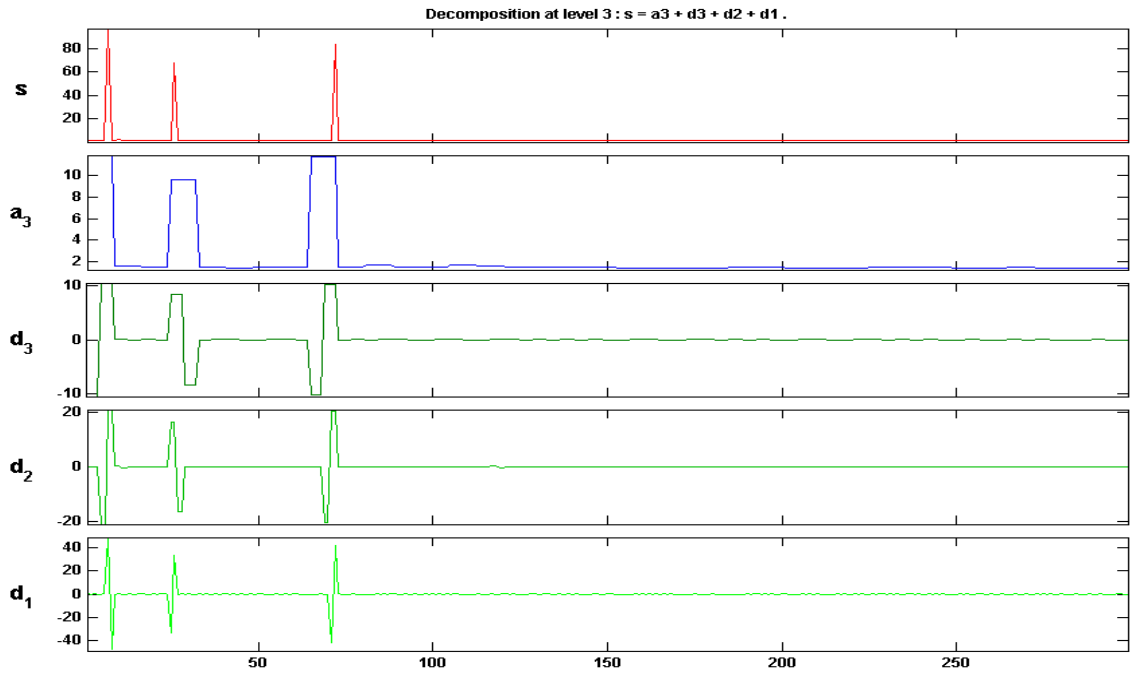


Figure 3.66: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=3760V$ & $H=75\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. The event corresponding to the detail coefficient d_1 and d_2 are illustrated in Figure 3.66, for bentonite. The values of the current flow are nearly zero except at the instant the current peaks where d_1 changes between 40A and -30A for a duration of 0.2s are observed.

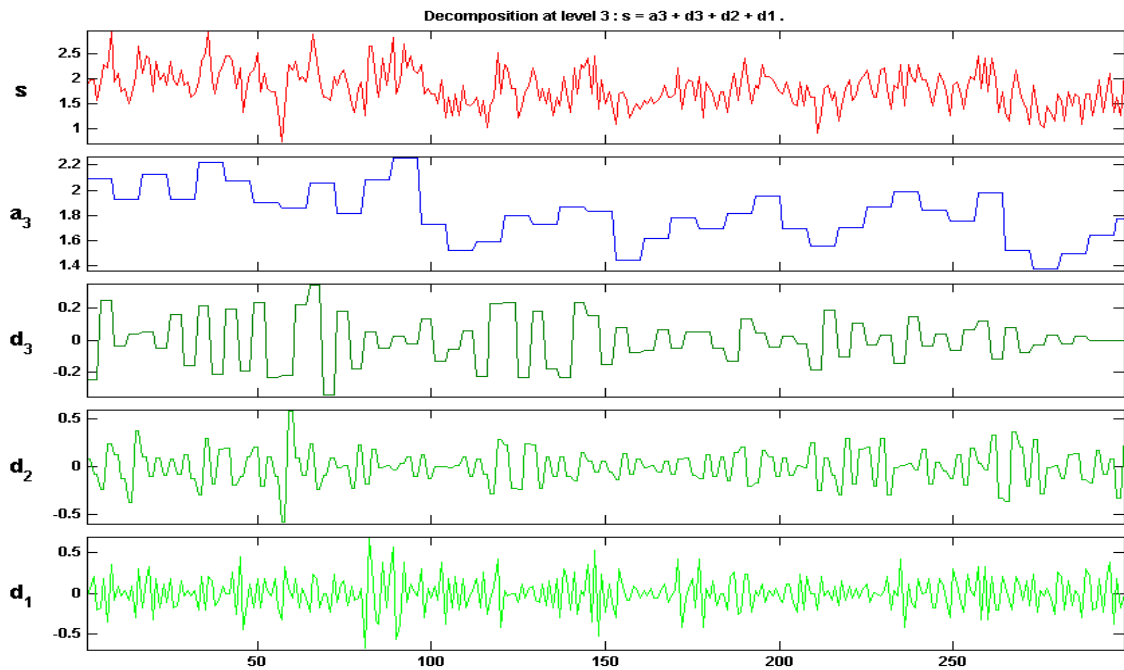


Figure 3.67: DWT based decomposition of the dissipated current signal in the soil for NG at $V=3760V$ & $H=75\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. The event corresponding to the detail coefficient d_1 and d_2 are illustrated in Figure 3.67 for natural enhancement material. The values of the current flow are nearly zero with d_1 changing between $0.5A$ and $-0.5A$.

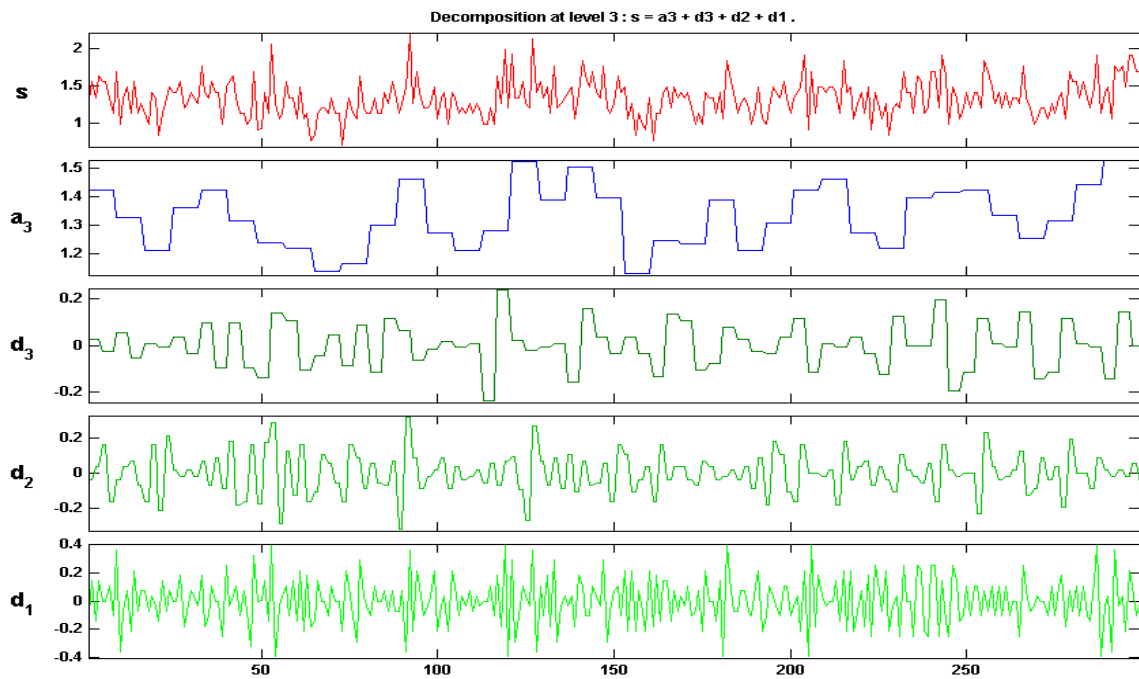


Figure 3.68: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=3760$ V & $H=75\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. No lecture is possible due the noise.

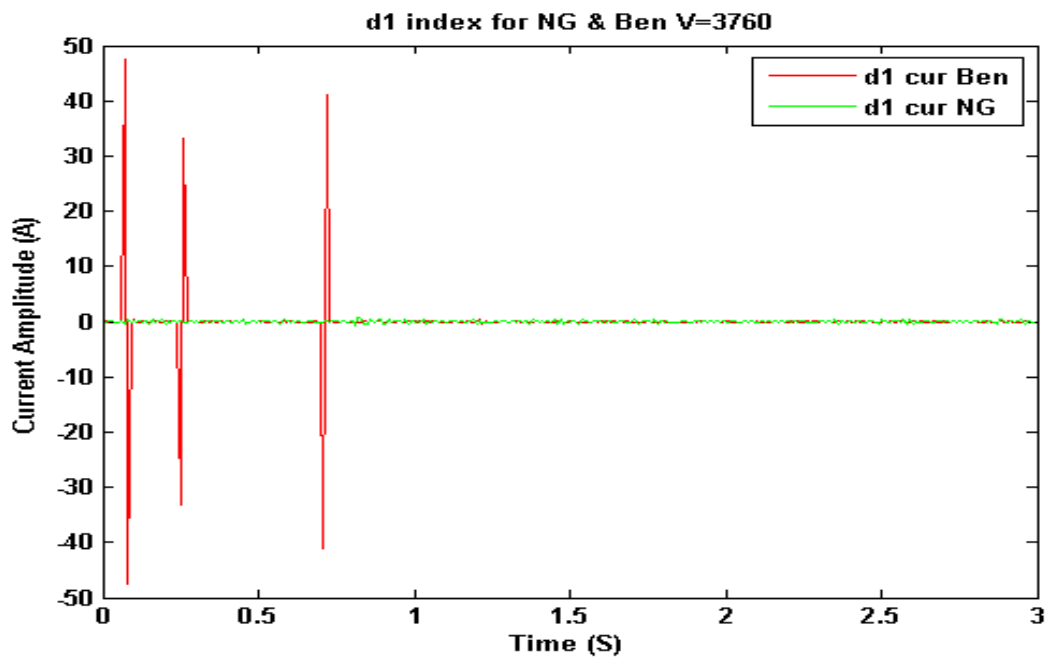


Figure 3.69: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at $V=3760$ V and $H=75\%$.

Figure 3.69 shows after the highest peak have been recorded only one event occurred at $t=0.052s$ with a magnitude of 50 A for the bentonite. As for the natural enhancement material, Figure 3.69 has shown the event that happened is too small to read. The bentonite peak duration has decreased from 0.24s to 0.2s. The dissipation time for the highest fault current has reduced as the humidity has increased.

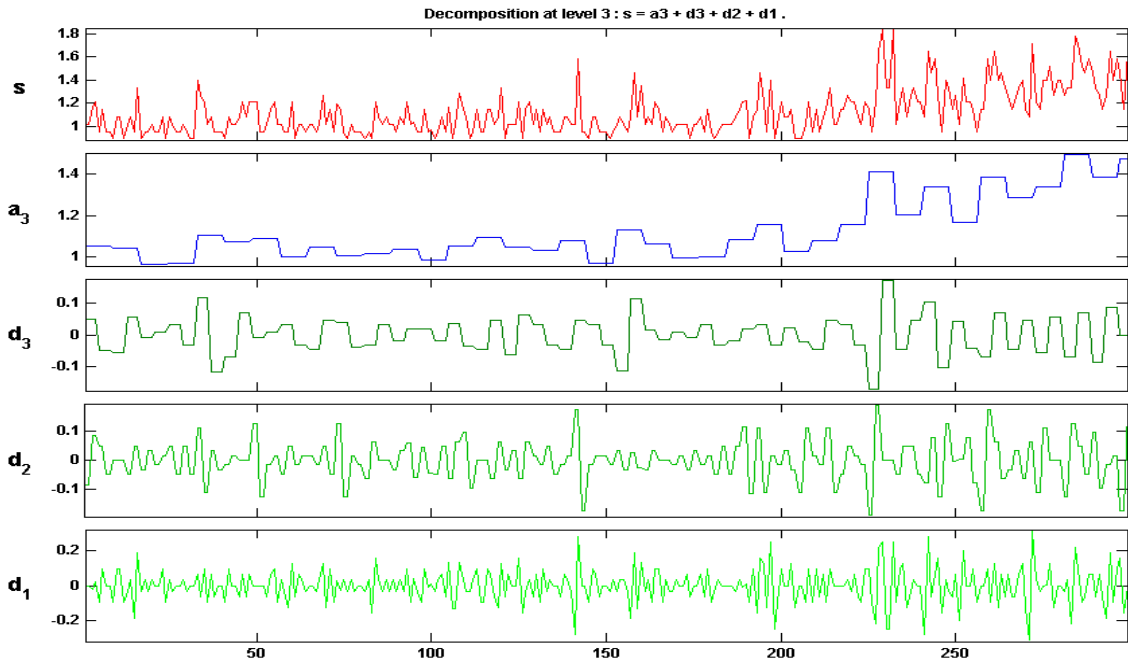


Figure 3.70: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=2050\text{ V}$ & $H=76\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

The event corresponding to the detail coefficient d_1 and d_2 are illustrated in Figure 3.70 for bentonite. The values of the current flow are nearly zero with d_1 changing between 0.2A and -0.2A. No high peaks are detected in the first half of the measurement.

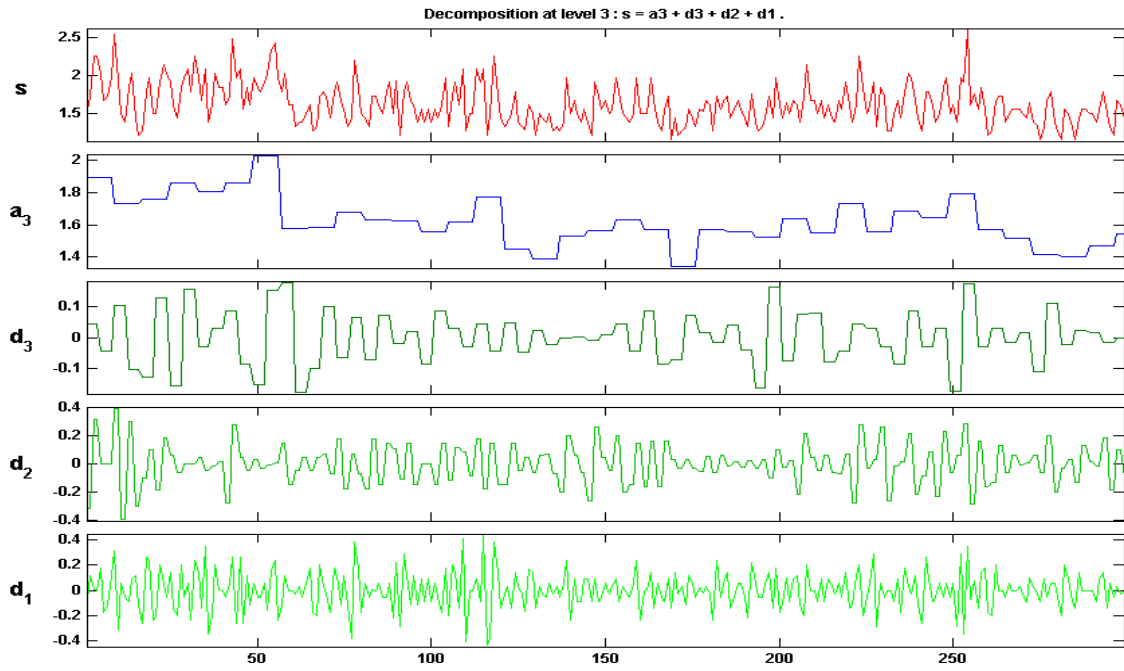


Figure 3.71: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2050$ V & $H=76\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3., 2. and 1. respectively. The analysis of Figure 3.71 shows multiple events have occurred during the experiment time with 2 peaks recorded. The magnitudes of the d1 change from 0.5A and -0.5 A for the big event.

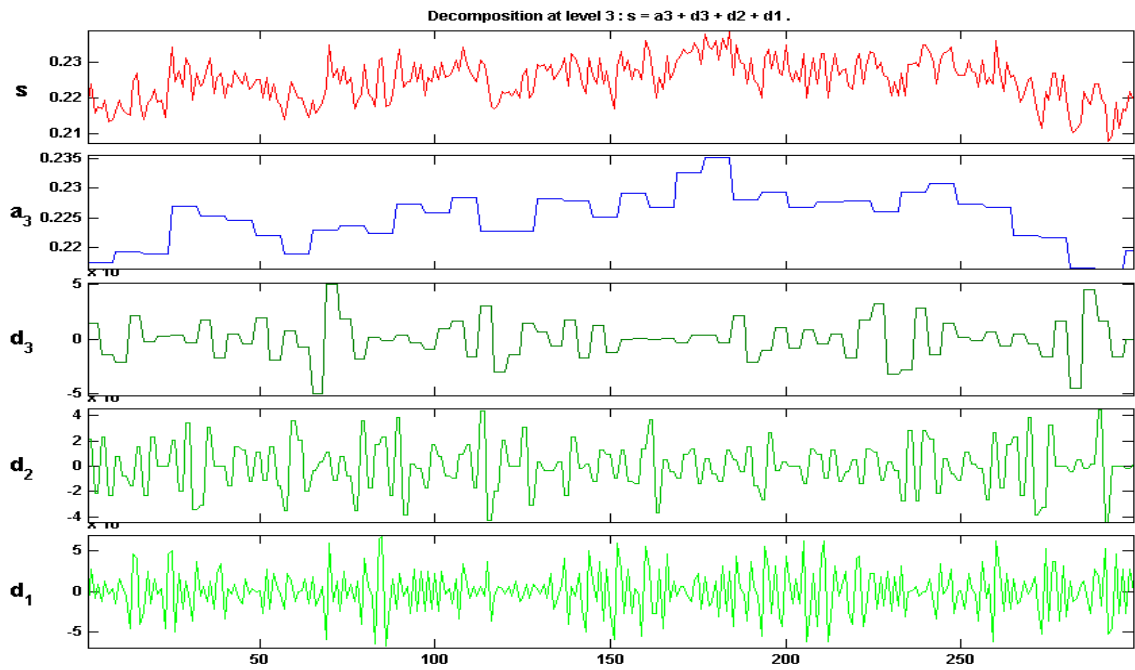


Figure 3.72: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V= 2050$ V & $H=76\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively.

Figure 3.72 depicts multiple events with the highest peak of 5 A happening at $t=1.12$ s

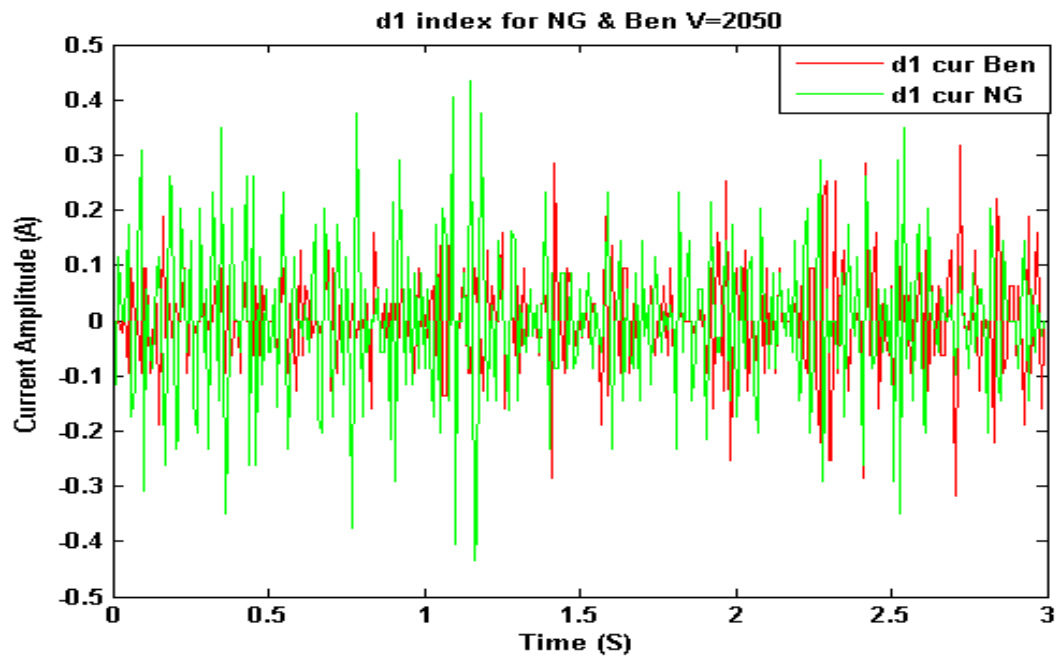


Figure 3.73: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V= 2050 V and H=76%.

Figure 3.73 presents the first decomposition level for both natural enhancement material and the bentonite. Both registered an increase in the dissipation path as the humidity increased. As shown in Figure 3.69 and Figure 3.73, it is noticeable that the number of discharge signals has increased compared to the analysis of H=75%. There is a similarity in the behaviours for both materials and the duration of their highest peaks. Based on these readings, the findings show that the bentonite performance depends on the humidity level.

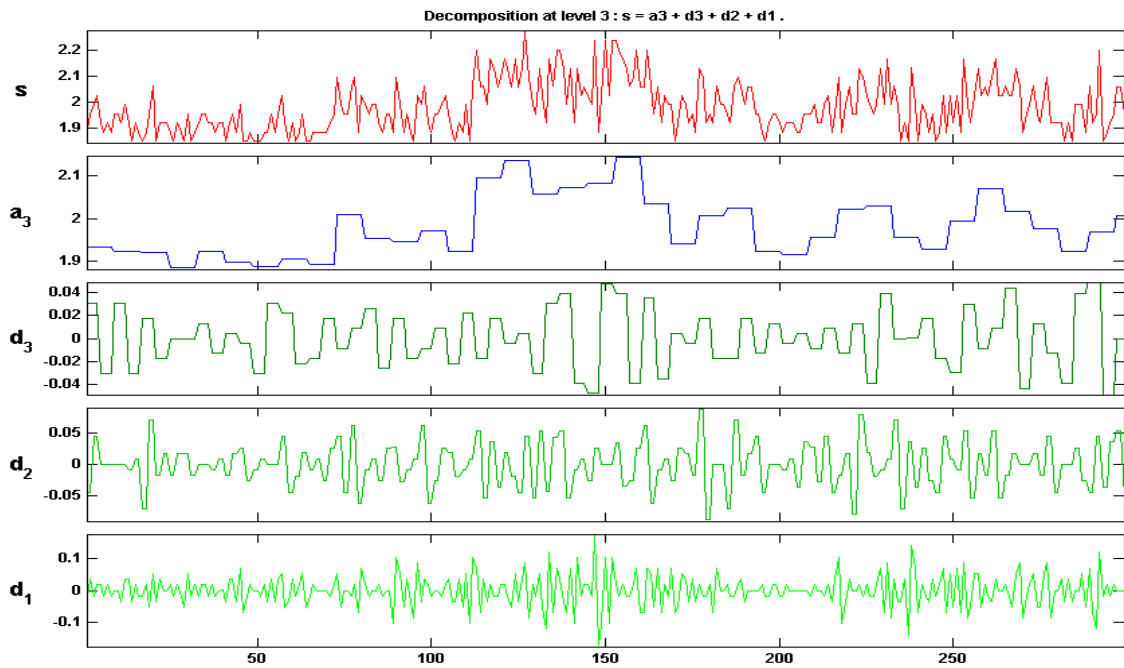


Figure 3.74: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=2670$ V & $H=76\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. In Figure 3.74, a peak of amplitude 20 A is recorded for the bentonite. The rest of signal dies out to zero for the rest of the measurement.

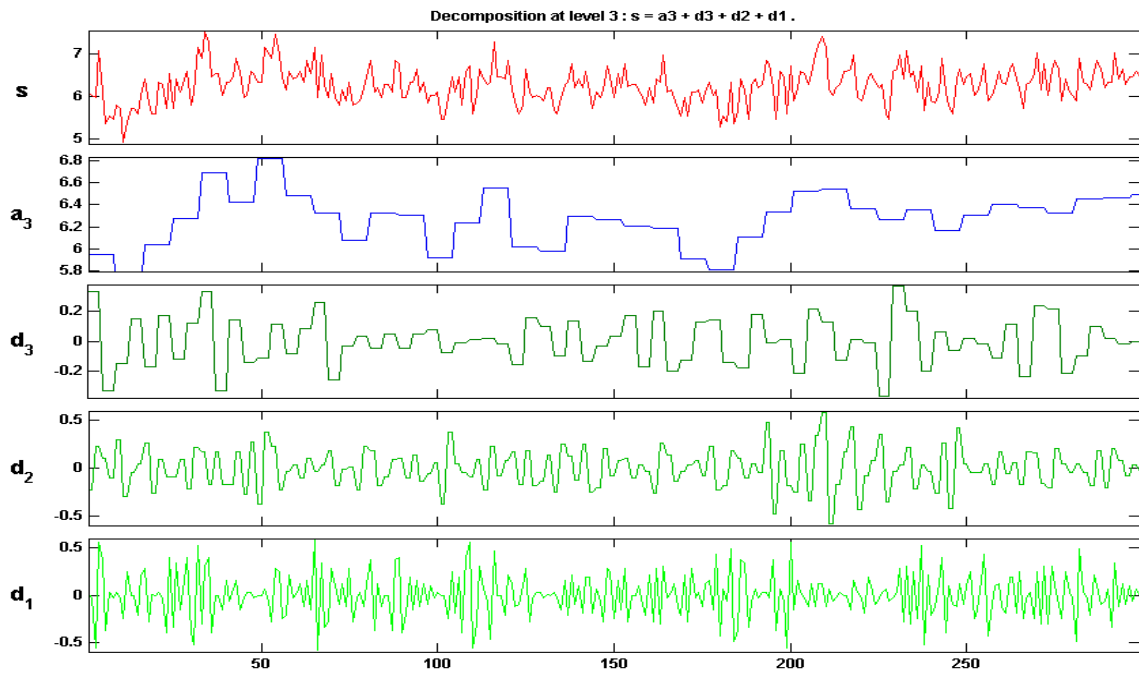


Figure 3.75: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2670$ V & $H=76\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively.

The details coefficients for bentonite d_1 and d_2 present in Figure 3.75 shows multiple discharges over the 4.8s. The discharge magnitude d_1 varies between 0.5A and -0.5A at $t=1.86$ s to 6A at $t=4.2$ s with the highest peak duration of 0.27s.

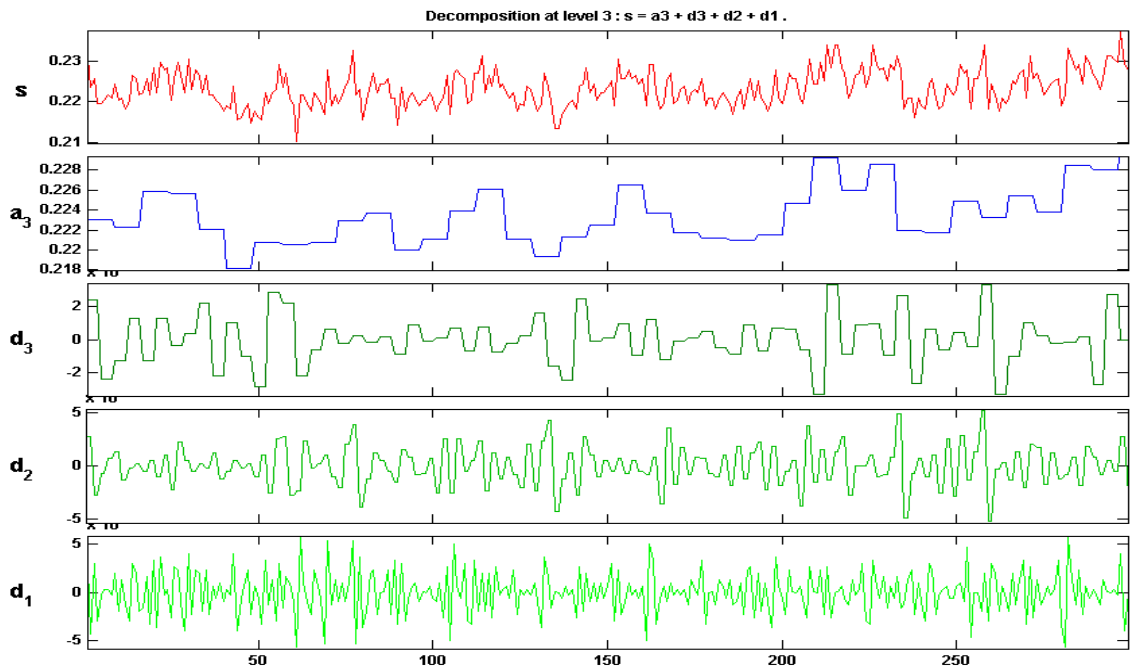


Figure 3.76: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2670$ V & $H=76\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively. The details coefficients for bentonite d_1 and d_2 present in Figure 3.76 shows multiple discharges over the 4.8s. Few discharges points can be seen with an amplitude of 5A.

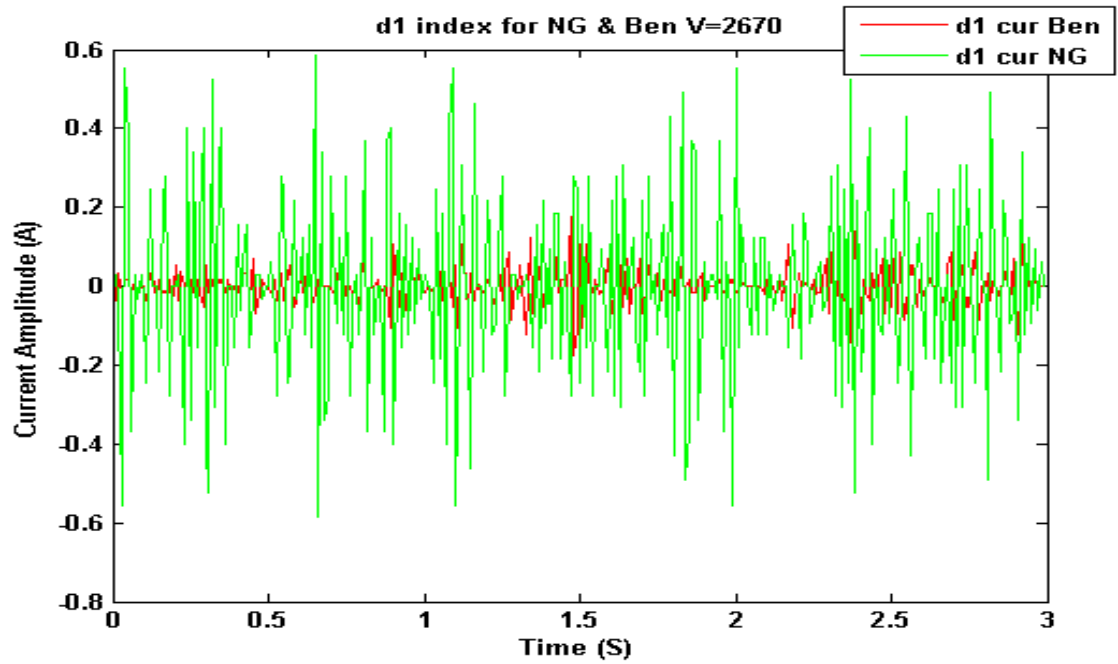


Figure 3.77: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=2670 V and H=76%.

The natural enhancement material highest peak time ($t=0.1s$) happened quicker with higher magnitude than the bentonite. The values of the first DWT decomposition d_1 are almost null except for the moments for discharge. During the first 3 s the natural enhancement material registered the most electrical discharge. Result in Table 11-b shows similar patterns.

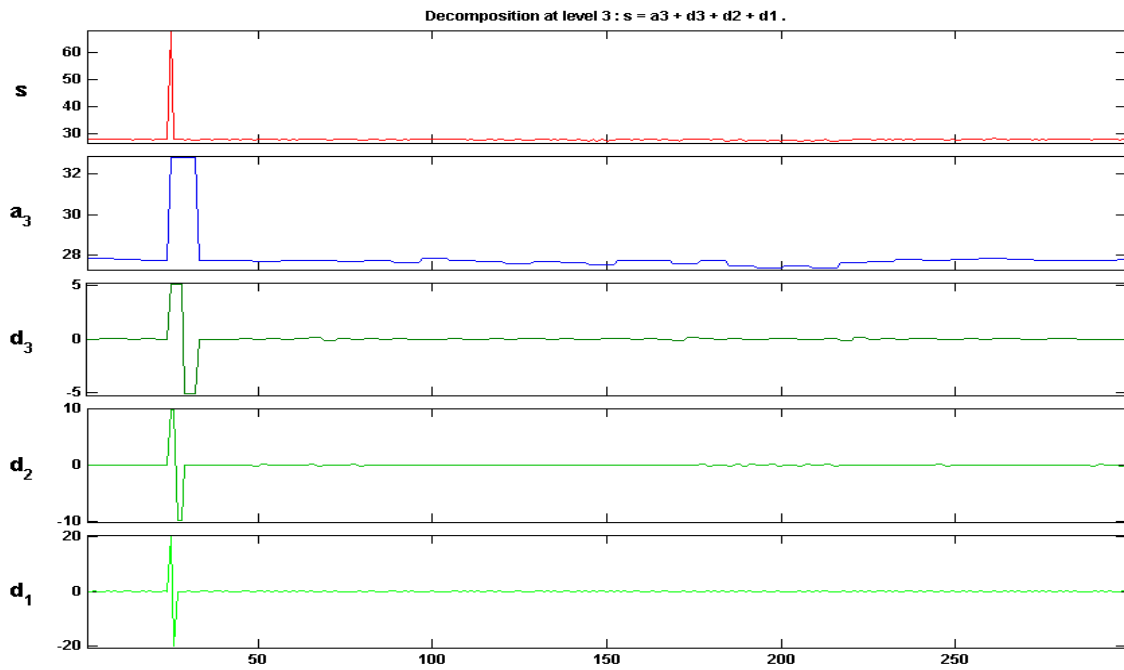


Figure 3.78: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=2900$ V & $H=76\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. In Figure 3.78, a peak of amplitude 20 A is recorded for the bentonite. The rest of signal dies out to zero for the rest of the measurement.

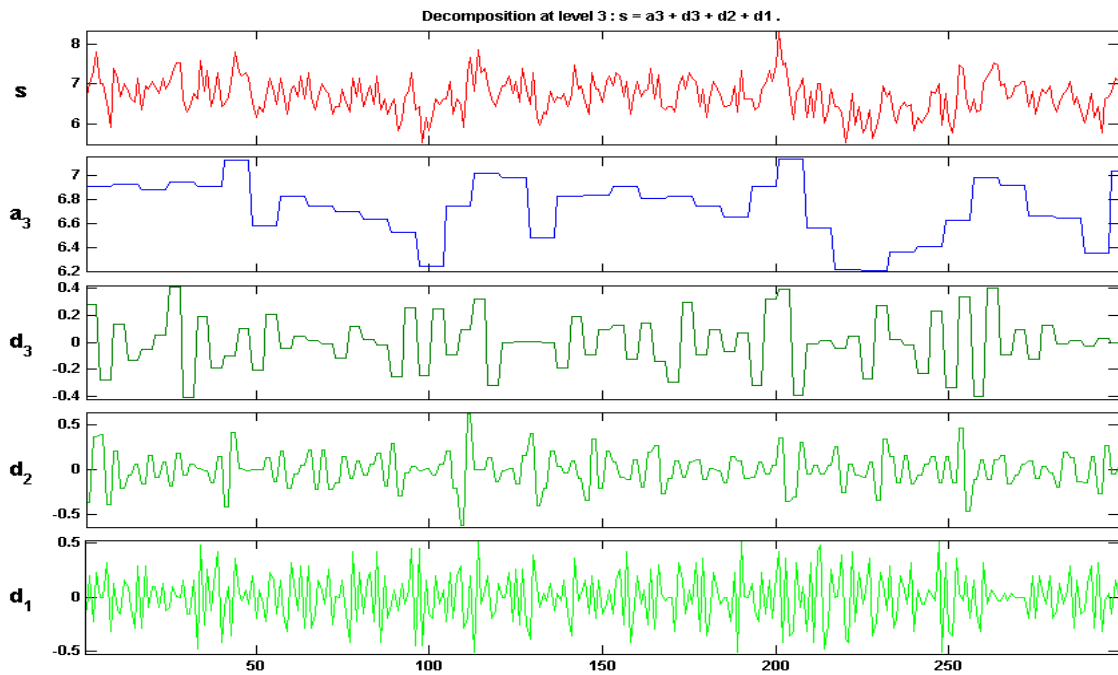


Figure 3.79: DWT based decomposition of the dissipated current signal in the soil for NG at $V=2900$ V & $H=76\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. The event corresponding to the detail coefficient d_1 and d_2 are illustrated in Figure 3.79 for natural enhancement material. It can be seen that the values of the current flow are nearly zero.

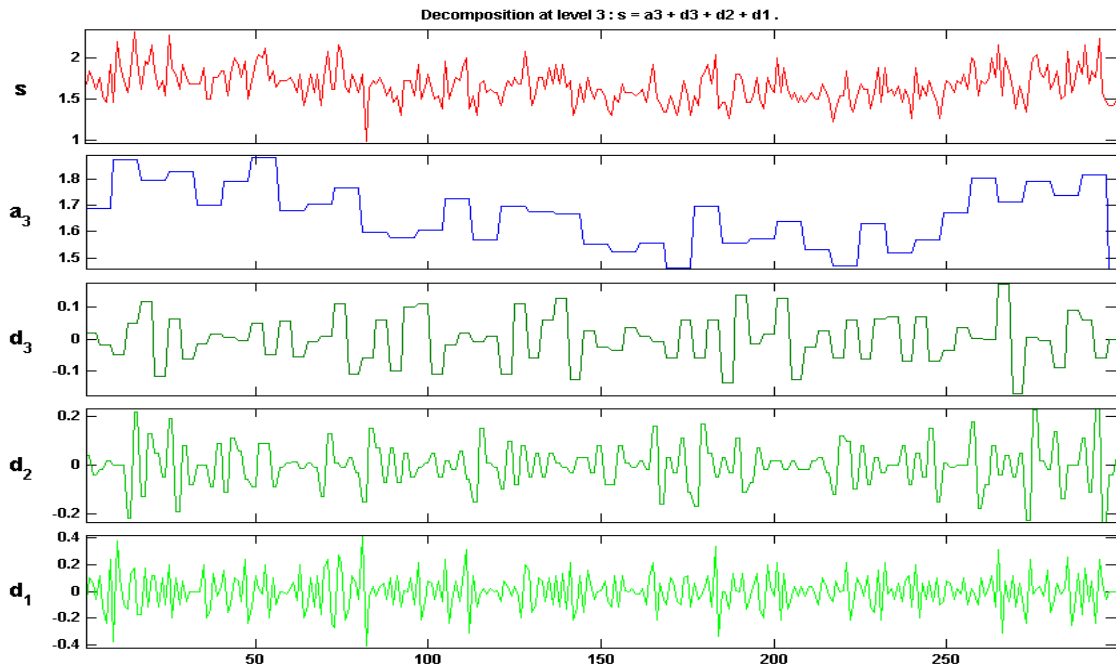


Figure 3.80: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=2900$ V & $H=76\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively. No lecture is possible due the noise.

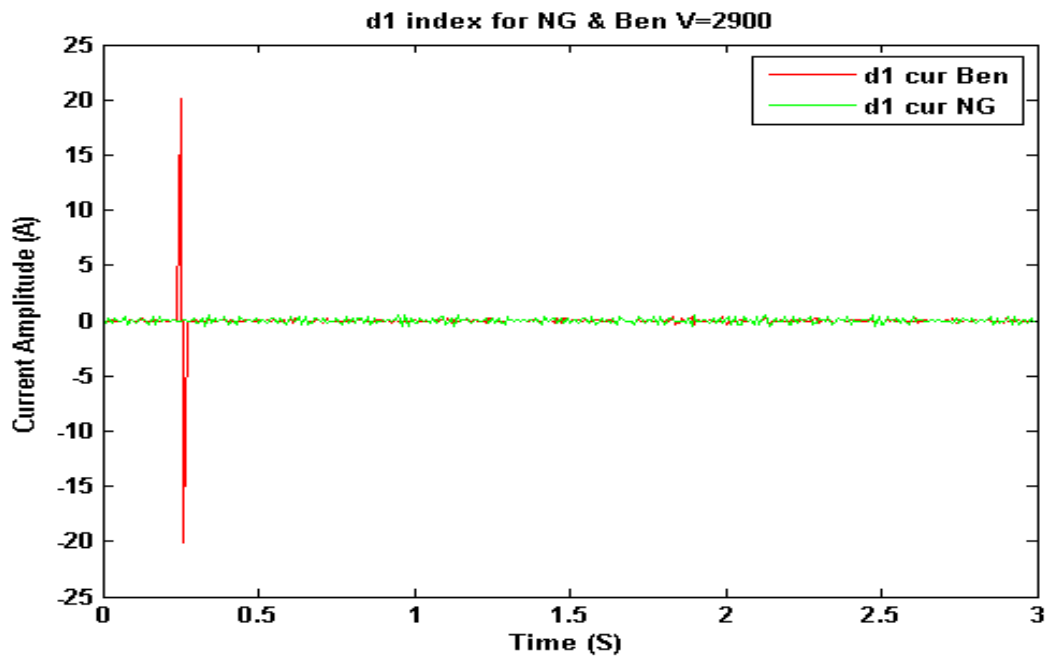


Figure 3.81: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V=2900 V and H=76%.

Figure 3.81 shows a peak taking place, with a magnitude of 20A for bentonite. As for the natural enhancement material, has shown the events that happened are relatively small compared to the events for the bentonite. Table 11 shows the same result.

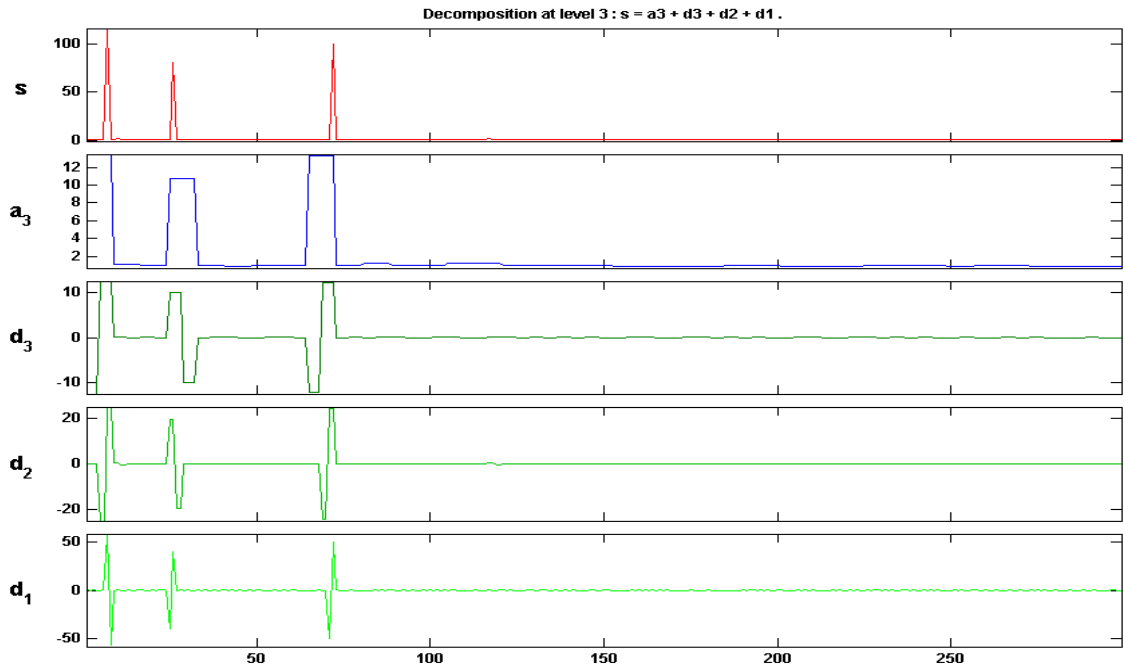


Figure 3.82: DWT based decomposition of the dissipated current signal in the soil for bentonite at $V=3760$ V & $H=76\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively. The event corresponding to the detail coefficient d_1 and d_2 are illustrated in Figure 3.82 for bentonite. The values of the current are nearly zero except at the instant the current peak with an amplitude of 60A for a duration of 0.178s (d_1 varying 50A and -40A) and a smaller peak at $t=1.05$ s with an amplitude of 35A (d_1 varying 35A and -35A).

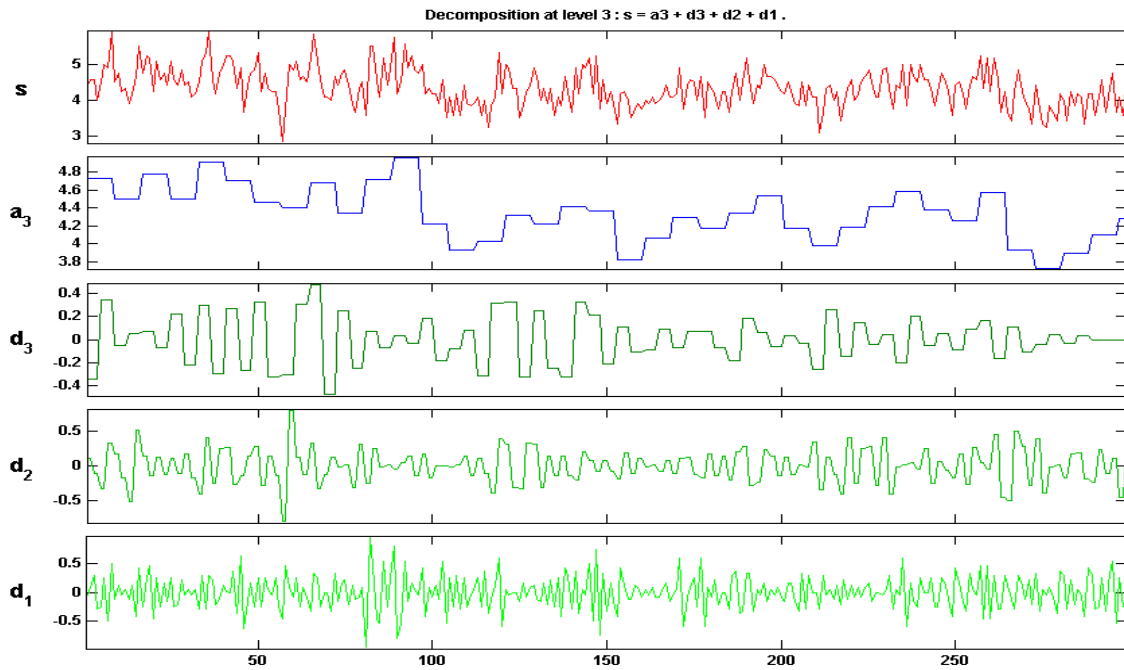


Figure 3.83: DWT based decomposition of the dissipated current signal in the soil for NG at $V=3760$ V & $H=76\%$. (s) Original current signal (a_3) approximation coefficient of 3. Decomposition level (d_3), (d_2) & (d_1) are detail coefficients of level 3, 2, and 1, respectively. The event corresponding to the detail coefficient d_1 and d_2 are illustrated in Figure 3.83 for natural enhancement material. It can be seen that the values of the current flow are nearly zero.

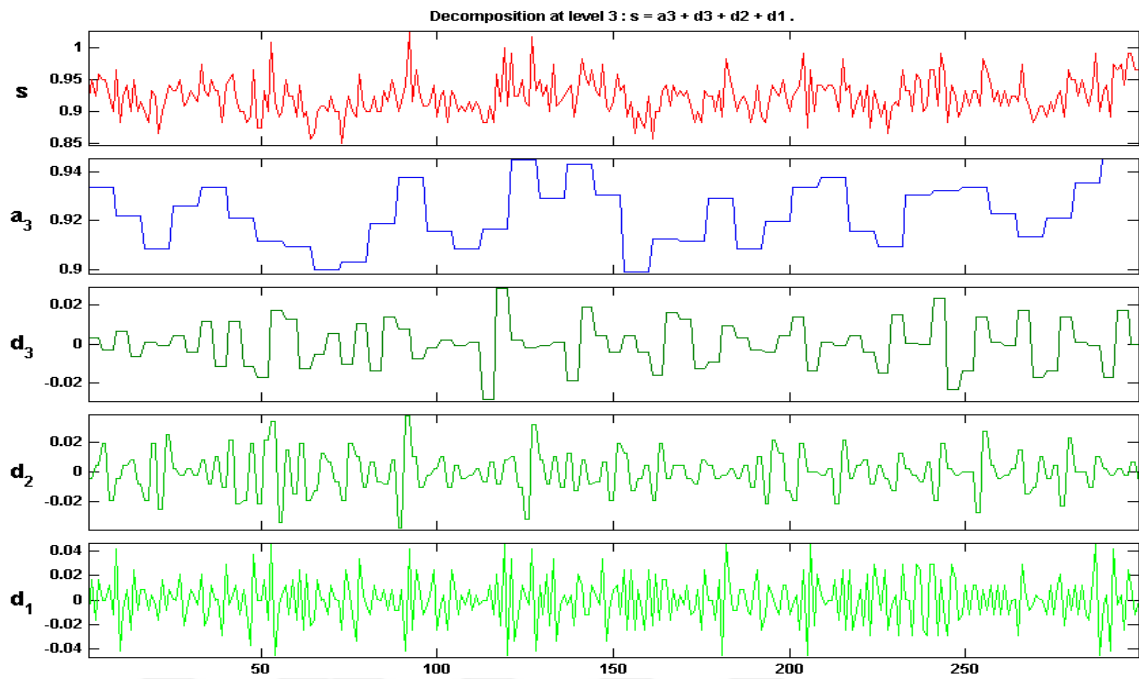


Figure 3.84: DWT based decomposition of the dissipated current signal in the soil for normal soil at $V=3760$ V & $H=76\%$. (s) Original current signal (a3) approximation coefficient of 3. Decomposition level (d3), (d2) & (d1) are detail coefficients of level 3, 2, and 1, respectively. No lecture is possible due the noise.

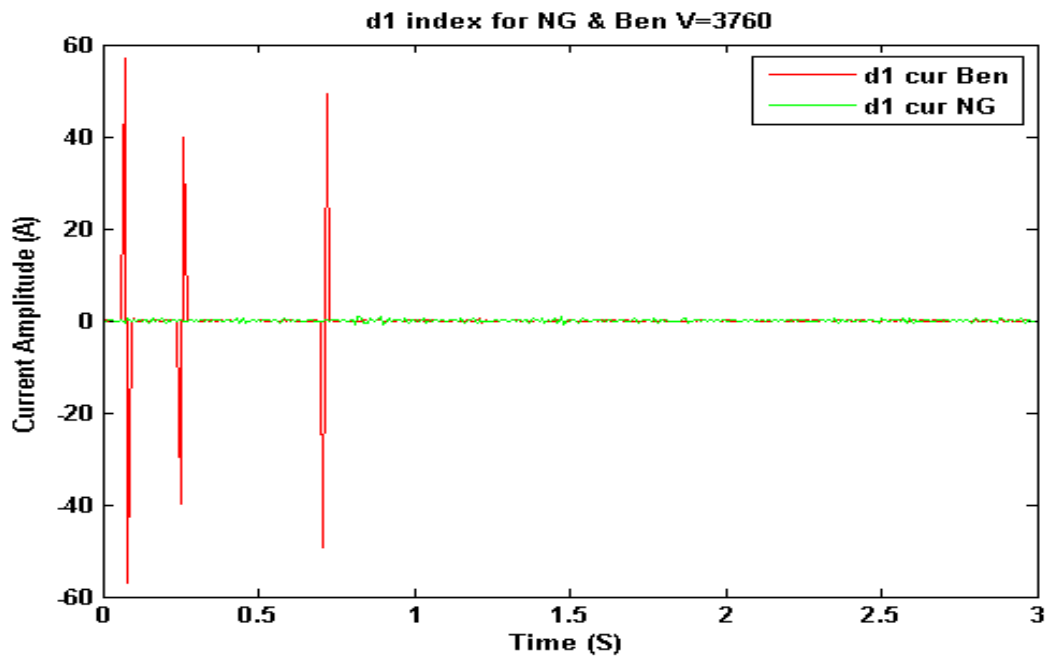


Figure 3.85: DWT based decomposition of the dissipated current signal in the soil for bentonite & natural enhancement material and the soil at V= 3760V and H=76%.

Figure 3.85 shows after the three peaks taking place, one at $t=0.025$ s with a magnitude of 60A and the others at $t=0.25$ s & $t=0.6$ s with an amplitude of 40 A and 50A respectively for bentonite. As for the natural enhancement material, Figure 3.83 has shown the events that happened are relatively small compared to the events for the bentonite. Relatively to the observation in Figure 3.85 for high humidity level bentonite is safer.

4. DISCUSSION

Natural enhancement material is becoming trending in the green engineering domain, because of the fast climate change and its effects on the planet's life. Resourcing and finding new material, new methods to reduce our carbon footprint is crucial. Following that optic, it is decided to use Palm oil as it is massively produced in West Africa and a very common product. It has been used as a natural GEM in the past and also participates in the fabrication of Power cables [4,19]. A set of quality parameters (acidity free, water content, insoluble matter content) led the scientists to choose palm oil waste as a good candidate for NGEM [64]. The coconut peat fiber besides its hygroscopic nature acts as resistors in parallel in the mixture. Thus it decreasing the overall resistance of the cake. Coconut fiber was also used by Aizat Azmi and al as a structure to keep moisture [4]. The Aluminum and iron powers were added to increase the conductivity within the structures of the mixture. The whole mixture was enclosed in concrete to keep it compact. The dosage of each material was decided based on our investigation through the literature and it was improved with the experiment until the optimum dosage was established.

DWT helps to uncover signal patterns that may be difficult to perceive in the normal analysis method. The graphs obtained from DWT show different peaks on the different intervals in times which allow determining the moment a fault happens in the system and the magnitude of the fault. For these reasons, DWT was chosen for the study to have a clear representation of the behaviors of each material under different impulse stresses. Approximation coefficients which capture low-frequency information of the signal were ignored in the analysis. The focus of the analysis was based on the detail coefficients (high-frequency information) as we are dealing with the transient. The representations of the d1 indices for the bentonite show throughout the experimentation that the bentonite performance depends on its environmental conditions of it surrounding (Humidity/ temperature level). Considering the DWT reading for H=68% for the bentonite, the d1 values become impact only at V=3760 V. This is proven in Table 8 and also by V. P. Androvitsaneas, I. F. Ganas, and I. A. Stathapulas, the bentonite performs better in high humidity [22]. NGEM performance increases as the humidity and the impulse voltage levels increases. In figures 3.9, 3.13 and 3.17, d1 indices show increasingly high oscillation around certain times. At H=68% one high peak was recorded for Figure 3.9/V=2050 V and 3 peaks for Figure 3.13/V=2600 V and multiples peaks for Figure 3.17 . The voltage stress

increases the multiple discharge paths are created in the soil for the fault current to dissipate. Similar patterns are recorded for the other voltage stresses.

For $H=70\%$ is mostly dominated by the appearance of multiple high oscillations peaks on d1 graphs for the bentonite. As the impulse voltage level increases the level of the transient current recorded for the bentonite increased relatively and multiple narrow discharge paths were noticed in Figure 3.25, 3.29, and 3.33. NGEM on the other hand performs better than in $H=68\%$ with the existence of early high discharge paths since $V=2050V$.

For $H=72\%$ and 75% , the performance of the bentonite has increased drastically with the presence of multiple oscillations. Clearer high discharge peaks are observed for $H=75\%$ and 76% . The transient's current magnitudes are extremely high reaching over $50A$ for the bentonite Figure 3.69 and Figure 3.85. The moisture level indicates the high performance for bentonite with a bigger transient dissipation path.

Stopping at a mere observation of the soil reduction capacity of a material is not enough to call it, a great backfill material. The discharge times and the discharges points of each material should also be considered. As an example, although in Table 7.a at $V=2050 V$, bentonite has a higher soil reductive capability, but considering the DWT d1 analysis in Figure 3.6 and Figure 3.7, NG has the quickest and the highest dissipation time and discharges points

5. CONCLUSION AND RECOMMENDATIONS

This study provides useful information for the design and the behavior of a grounding system encased in natural enhancement material and bentonite under high impulse voltage. It also gives information about protection measures in electrical installation from lightning strikes and highlights the multiple benefits of using grounding enhancement materials and their effect at high impulse conditions. For this purpose, 3 grounding rods, each encased in either bentonite, natural enhancement material, and normal soil have been tested. From the results, the following outcomes are obtained through impulse tests:

- Both natural enhancement material and bentonite have significantly reduced the transient impedance around the grounding Rod1 and Rod2 with respect to Rod3.
- Natural enhancement material has a higher resistivity reduction and the shortest fault current dissipation duration in low humidity levels and low voltages compared to bentonite.
- On average, bentonite showed better performance compared to natural enhancement material, but it seems to perform satisfactorily only in high humidity and humid climates.
- Natural grounding materials have shown no hazardous effect on the surrounding grounding system and also perform satisfactorily for both low and high humidity levels.
- The bentonite presents slightly better performance than the natural enhancement materials. The difference between them is around 10%.

Natural grounding materials are an effective method for soil treatment in the grounding system and they obey the safety measures in IEE 80 standard.

More work needs to be done for different soil types and different transient levels, to fully comprehend the behaviors of ground enhancement materials under impulse conditions. With this study, it is shown that the impact of climate conditions must be considered in order to design a good grounding system.

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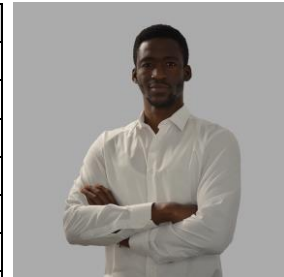
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