Course name: EMI /EMC and Signal Integrity: Principles, Techniques and Applications.
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Week :12
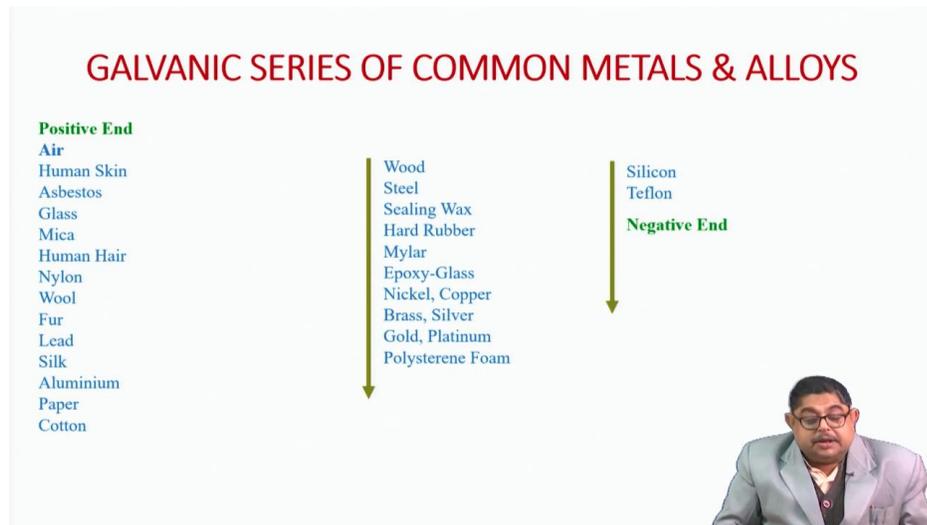Lecture 59: Electrostatic Discharge (ESD)

Welcome to the or the final lecture of the course on EMI EMC and Signal Integrity Principles, mechanics and applications. We have elaborately discussed various system aspects of EMC. Now, today we will see the electrostatic discharge, this also comes under electromagnetic compatibility. So, ESD we will discuss. Now, first how ESD is created? ESD results due to separation of static charges. So, here no electromagnetic wave is initially involved ESD when two different types of static charges are separated ESD results. So, how to create ESD? You rub two materials obviously insulating because in conductors if you rub nothing will happen. So, two insulating materials and then separating them. So, two opposite charges on two bodies get created creates an intense electric field between the two bodies two separated bodies creates an which in turn creates an intense potential difference may result in breakdown of intervening air which if happens will results in arc discharge. Also if one of the charged insulator comes in contact with a conductor charges may enter via conductor to electronic circuit. For vacuum tubes high tubes it is stops. So, there is a type graphical error for vacuum tubes high field needed to cross the barrier for semiconductor device unfortunately small field may cause the damage that is why ESD is very problematic in semiconductor industry. Susceptibility of an electronic product to ESD is required.

Creation of ESD
- ESD results due to separation of static charges
- Ways of creating ESD:
a) Rubbing two insulating materials and then separating them
b) Two opposite charges on two bodies:
  - creates an intense electric field
  - creates an intense potential difference
  - may result in breakdown of intervening air
  - results in an arc discharge
c) Also if one of the charged insulator comes in contact with a conductor
  - Charges may enter via conductor to electronic circuit
  - For vacuum tubs high field needed to cross the barrier
  - For semiconductor devices, small field may cause the
- Susceptibility of an electronic product to ESD is require

Now, there is a galvanic series of common metals and alloys. So, there is a positive end there is a negative end. So, if you rub any of these with the other you will get the and then if you separate the one higher in the series that will get the positive charge and the lower one will get the negative charge. So, if you rub you see human hair and wool human hair will get positive charge and wool will get negative charge because human hair is up in the series compare to wool.

GALVANIC SERIES OF COMMON METALS & ALLOYS

Positive End
Air
Human Skin
Asbestos
Glass
Mica
Human Hair
Nylon
Wool
Fur
Lead
Silk
Aluminium
Paper
Cotton

Wood
Steel
Sealing Wax
Hard Rubber
Mylar
Epoxy-Glass
Nickel, Copper
Brass, Silver
Gold, Platinum
Polysterene Foam

Silicon
Teflon

Negative End

So, this phenomena is called triboelectricity two insulators are placed in contact charge may be transferred from one to other when the two bodies are separated they become oppositely charged those at positive end give us give up electrons easily and become positively charged rubbing rubber with wool and separating rubber will be negatively charged let us see in the series rubber with wool. So, where is rubber this is rubber and wool is much above. So, wool will get positively charged rubber negatively charged. So, you see rubber will be negatively charged. So, wool will be positively charged .

CHARGE SEPARATION IN TRIBOELECTRICITY

• Two insulators are placed in contact, charge may be transferred from one to other. When the two bodies are separated, they become oppositely charged.

• Those at positive end, give up electrons easily and become positively charged.

• Rubbing rubber with wool and separating : Rubber will be negatively charged.

triboelectric the galvanic series or triboelectric series indicates which type of charge will which body will get, but the quantity it does not give the degree to which charge will be transferred depends on a number of factors. That means,   the quantity depends on smoothness of the surface cleanliness of the surface contact surface area contact pressure degree of rubbing how much you rubbed and speed of separation   all these are factors which affect the quantity of charge that will be created.

QUANTITY OF CHARGE TRANSFER

- The degree to which charge would be transferred depends on a number of factors:
  - ➤ Smoothness of the surface
  - ➤ Cleanliness of the surface
  - ➤ Contact Surface area
  - ➤ Contact pressure
  - ➤ Degree of rubbing
  - ➤ Speed of separation etc.

- Triboelectric series only indicates the nature of charge, not it's amount

 Now, conductor and insulator one when you instead of two insulators if you use one insulator and one conductor placed in contact when they are separated they will also produce opposite   charges according to the triboelectric series, but the charge in conductor when alone gets redistributed over the whole surface in relation to conductors relaxation time. Relaxation time means when the any impressed field is created that time charge have one distribution, but when that is removed the within relaxation time the charge gets redistributed according to the conductors shape size etcetera, but for the insulator it stays in the original position. So, this is the difference between charges in conductor and charges in insulator grounding a conductor will take all these charges to ground. So, but if you ground an insulator it will not. So, these are the differences between conductor and insulator their static charges.

CONDUCTOR AND INSULATOR

- One insulator and one conductor can be placed in contact. When separated, they will also produce opposite charges according to the triboelectric series.

- But the charge in conductor, when alone, gets redistributed over the whole surface in relation to conductor's relaxation time. But for the insulator, it stays in the original position.
- Grounding a conductor will bleed off the charge to ground

- Grounding an insulator will not

Now, voltage due to charge separation. So, voltage developed obviously when two bodies are oppositely charged there will be a voltage drop. So, one by one how it is happening that we are described in this slide. So, there are opposite charge on the objects. So, there will be a capacitance between the two objects and voltage is capacitance by the charge. Suppose two materials are in contact charges transfer then materials are separated the charge remains on the materials the. So, the charge does not get changed it cannot change, but the voltage changes because when you separate that time the capacitance of the system gets changed that is why the voltage gets changed.

For a given amount of charge for close separation capacitance is large and so the voltage will be small because of this formula capacitance if it is large Q is fixed. So, voltage will be small for on the other hand for large separation capacitance is small. So, voltage is large a typical example is a charge separation of one micro coulomb associated with a capacitor of 100 pico farad gives 10 kilo volt voltage difference. You see only a one micro coulomb charge with a capacitor of 100 pico farad is typical. So, we will see that human body has that type of capacitance. So, you can see that with a one micro coulomb charge we can have a voltage of 10 kilo volt. You see here breakdown electric field is 10 kilo volt per centimeter. So, that means the arc will be produced and the electric discharge arc will be produced if we get 30 kilo meter per centimeter field. 10 kilo meter if k v is your voltage generally does not breakdown, but if you increase the voltage and your separation of this human system if it is of the order of the centimeter. So, with 30 kilo volt per centimeter it will give you a discharge. So, sometimes you will see that in winter if you are combing your hair that time small amount of light comes actually those are from this electrostatic discharge air breakdown.

Interrelation of Voltage and Capacitance

For a given amount of charge
- For Close Separation
  - Capacitance is Large
  - So, voltage is small
- For large separation
  - Capacitance is small
  - So, voltage is large

- A charge separation of $1\,\mu C$ associated with a capacitor of $100\,pF$ gives $10\,kV$ voltage difference

- Air breakdown electric field is $30\,kV/cm$

Now, capacitance depends on capacitor geometry also on field, but here we are assuming that intervening field is air, but intervening field medium if it change capacitance also change here we are not considering that. Capacitance is normally thought of as being between two bodies. So, you know capacitance between two parallel plates of area A that are separated by a distance d in air neglecting fringing of the fields at the plate is that means we are assuming that the plates are large plates. So, c is equal to epsilon naught A by d. So, that gives you 8.85 A by d in pico farad.

CAPACITANCE DEPENDS ON CAPACITOR GEOMETRY

- Capacitance is normally thought of as being between two bodies

- Capacitance between two parallel plates of area A that are separated by a distance d in air (neglecting fringing of the fields at the plate edges)

$$C = \epsilon_0 \frac{A}{d}$$
$$= 8.85 \frac{A}{d} \quad (\text{in } pF)$$

Now, capacitance between two bodies, but their shapes are two conductors spherical conductors concentric that means their centre is same, then the capacitance is given by this formula that means it depends on radius of the two spheres. Now, if in this formula r 2 goes to infinity then you get the capacitance of a single sphere because r 2 going to infinity means actually you can assume that the at infinite distance there is a conductor

which that means basically a single sphere. So, that time it is 100 and from this top formula you are getting this formula by putting r to infinity. So, it is 111 r in pico farad. So, obviously, here r should be in meters.

CAPACITANCE OF SPHERICAL BODIES

- Capacitance between two concentric conducting spheres,

$$C = \frac{4\pi\epsilon_0}{\frac{1}{R_1}-\frac{1}{R_2}} \; ; \qquad R_2 > R_1$$

- If $R_2 \to \infty$, capacitance of a single sphere is

$$C = 4\pi\epsilon_0 R$$
$$= 111R \; (\text{in } pF)$$

Now, we come to the problem that I was saying capacitance of human body. A human body can be modeled as a sphere of diameter 1 meter, 1 meter roughly is 3.3 foot. You see fat persons like us we can be modeled as a 1 meter sphere. So, we can use the previous formula and capacitance come to 55.5 pf. Typically, the human body capacitance if order of 50 to 100 pico farad. If the isolated human body is placed near other bodies there will be additional capacitance due to mutual capacitance between the two, but roughly the depending on the height, width etcetera a human body has 50 to 100 pico farad capacitance.

CAPACITANCE OF HUMAN BODY

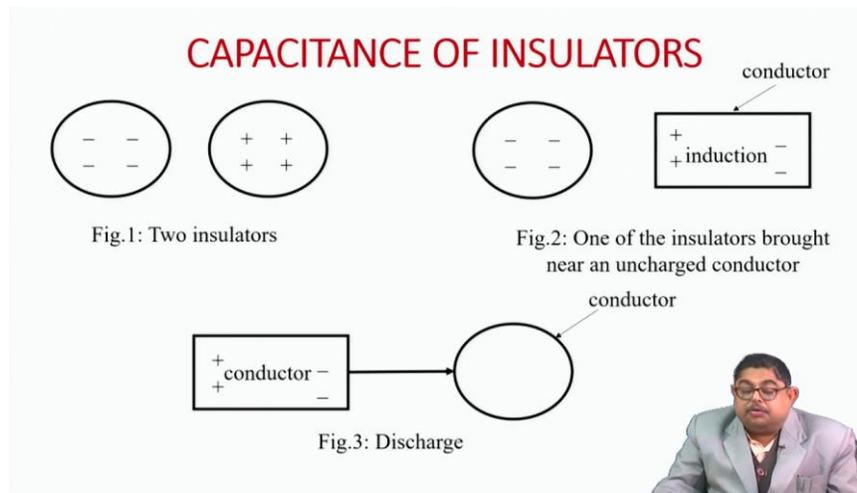- A human body can be modelled as a sphere of diameter 1 m.
  Therefore, $C = \frac{111}{2} = 55.5 \; pF$

- Typically, the human body capacitance $\sim 50 - 100 \; pF$

- If the isolated human body is placed near other bodies, there will be additional capacitance due to mutual capacitance

Now, you see capacitance of two insulators. So, from triboelectric series we can see that you can get that what are the two insulators and from that you can determine which one will be positive charge, which one will be negative charge. Now, figure 2 shows one of the insulators brought near an uncharged conductor. So, conductor will get by induction the positive charges they will go to the conductor. So, conduct also the negative charges at this end they will also go to the conductor then they will redistribute. So, that the positive charges at one end conductor and negative charges at another end. Then if you get the another conductor basically here we are not mentioning, but suppose this is generally done for discharge that means you connected to the ground. So, this second conductor this one is basically ground. So, if you connect them then this charges will come to the ground and if the potential is sufficient with the discharge you can also see a flash of light that means that time air breakdown also may occur not always provided if the electric field is of that order I said 30 kilo volt per centimeter you will also get breakdown, but if it is less this conductor from one conductor the charges will go to the next the other conductor.

CAPACITANCE OF INSULATORS

Fig.1: Two insulators

Fig.2: One of the insulators brought near an uncharged conductor

Fig.3: Discharge

Now, physics of discharge first you see the note ESD voltage discharge of less than 3.5 k B cannot be failed or seen by humans. So, 3.5 k B discharge is not at all problematic and nothing will be failed, but this is for human body, but it can create various functional problems or component destruction in electronic circuit that is why electronic foundry or space vehicle or satellite design centers they are very worry of this electrostatic discharge. So, you need to understand the physics. So, in winter suppose this is an example suppose sweater is taken of the body so, while taking sweater you those sweaters which does not have front buttons. So, you take it you take it off from your head that time your hair and sweater comes in contact. So, human hair that means wool rubs with hair let me. So, here let us see human hair and wool. So, human hair will be

getting positive charge wool will get negative charge. So, from turbo electro electric effect hair gets positive charge wool gets negative charge. So, as I said that hair gets positive charge. So, in human body hair is there and from our shape the our we if we think of as an conductor of electricity which definitely is because our whole nervous system etcetera they are working on this conductor the charge separation etcetera. So, our finger which is at the other end that gets negative charge. Now with our finger let us say we touch the refrigerator and we get a shock. So, shock means that means obviously you have a voltage more than 3.5 kv as I said that we have 10 kv. So, definitely we will get a typical human we will get a shock. Now we blame the refrigerator that the grounding is not proper, but actually it is well grounded through it our charges in the finger negative charges they are getting a path to go to ground and that time we are getting a shock because the voltage is more than 3.5 kv.

Now, charge body has a capacitance C with initial voltage V naught also the body has a resistance R obviously we are not perfect conductors. So, there will be some resistance and inductance also because there will be some body we can store as a magnetic form of energy. So, due to ESD that charge close to the product and through the neutral charge where it goes to the ground the neutral wire has an inductance L 2 because wire. So, any wire has an inductance.

So, instead of human body if a furniture get discharged suppose a furniture is connected to the ground. So, furniture has a charge now for furniture R is less than human discharge the furniture's resistance is less than human resistance. So, it produces an under damped waveform price time is typically 200 pico second to 70 pico second to 90 nano second pulse on time is typically 100 nano second to 2 micro second peak current is 10s of ampere voltage is 10 kilo volt. So, there are some differences between the resistance etcetera of these.

FURNITURE DISCHARGE MODEL

Instead of human body, if a metallic furniture discharges

- R is less than human discharge
- So, underdamped waveform
- Rise time $\sim$ 200 ps -70 ns
- Pulse on time $\sim$ 100 ns -2 μs
- Peak current $\sim$ tens of A
- Voltage $\sim$ 10 kV

So, this is the model. So, you can do a first order model of ESD you see the human body it has a resistance it has a initial charge. So, initial charge means a capacitor can only hold charge. So, there is a capacitor C and it is holding charge. So, that it is initially at a potential v naught with respect to ground there is a R L in series R is there the human body or furniture L 1 inductance we are calling L 1 and then that is connected to ground. So, while doing that there will be the electrostatic discharge. So, there will be a electrostatic current at the product with its neutral and neutral the product has a L 2 inductance and it is rounded. So, to ground this ESD current goes.

MODEL OF ESD (Contd.)
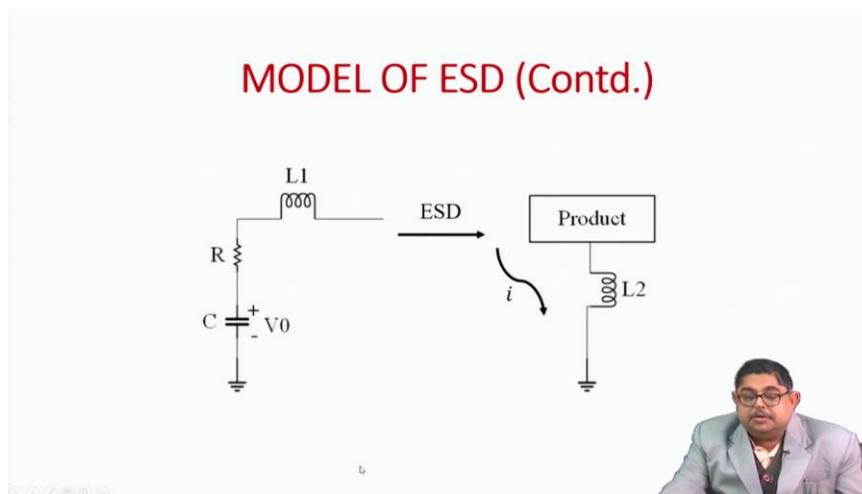
Now, what is the ESD waveform people have measured that this give rise to an over damped or under damped current waveform over damped in case of human discharge because it depends on R by L 1 you know that any second order waveform that has the there is a discharge whether it will be over damped or under damped is decided by minus R by L. So, R by L in case of over damped you see this is the ESD for furniture discharge R is less than human discharge. So, minus R by L L L 1 R by L 1. So, we will get a for human discharge and over damped because R is more for furniture discharge R is less. So, they will get an over damped case sorry they will get an under damped case.

So, human discharge you see that it is a over damped waveform and for furniture discharge you get an under damped basically the envelope is here e to the power minus R by L 1 it is e to the power minus R by L 2 is a envelopes discharge or that has the mathematical form e to the power minus whatever you can call it zeta or something generally people call. So, that. So, these are the ESD waveforms we have seen this waveform when we discussed about time domain electromagnetics that time also this was the waveform we have shown.

ESD WAVEFORM

This gives rise to an overdamped or underdamped current waveform

Overdamped
Human Discharge
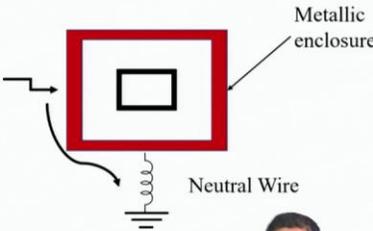
Underdamped
Furniture Discharge
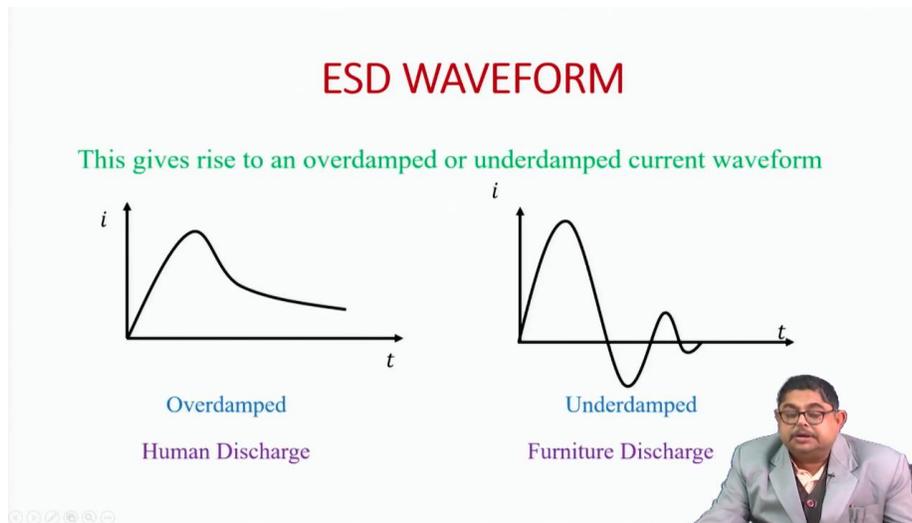
Now, how you will mitigate the ESD problem actually if you see the previous problems that you will have to this is in time domain you will have to see it is spectrum easily you can find it is spectrum unfortunately this spectrum has a sizable spectral content in the gigahertz range which is our micro wave range. So, in ESD though it is a static phenomena, but it is spectrum has sizable spectral components in the microwave spectrum that is the problem that is why it is comes we EMC engineers need to consider it and for that it is mitigation is needed. So, you see this red coloured box you see this red coloured box you see this red coloured box do it you enclose it and the black colour is your product and this red colour you put it under an enclosure metallic enclosure then

there will be obviously, you will have to put a neutral wire to the ground. So, ESD is coming. So, ESD current instead of entering the box it is seeing here a metal, but it is seeing the neutral wire. So, through this metallic enclosure immediately is goes to neutral wire it does not goes to the product. So, this metallic enclosure is directly connected by this wire to the ground. So, when ESD comes it comes here that waveform and immediately goes to ground the voltage of the metallic enclosure may rise to several kilo volt due to large inductance. So, there is a large inductance of this neutral wire that is why that voltage will be very high and that may rise the temperature of this metal wire, but no functional problem comes due to this. So, you will have to only see that the metal and metallic enclosure you will have to choose the metal. So, that it can withstand that high voltage. Now, one problem is that there may be penetrations because when this waveform is coming it may be some of them will leak through radiation path they will go here. So, obviously, that will create problem, but this is a first order mitigation solution. So, that is a second order problem. So, you will have to then find out how to do anything on the product. So, that penetration or radiation through this from metallic enclosure can be mitigated. So, ESD mitigation is not simple had it been simple EMC engineers would have lost their job because simply putting this metallic shield will would have solved the problem, but not so. So, we will have to think of other things that how this metallic enclosure can be made an inefficient radiator also. So, that it does not radiate. So, no penetration comes for that the knowledge you gained in radiated emission that will come in handy. I think this is this was all I had to say about EMC and we have covered a huge course both theoretic with theoretical depth also with information breadth. So, those are few topics could not be covered due to paucity of time one was lightning. Lightning is a then p static I did not cover then tempest I did not cover, but those are which I covered compared to them they are less significant, but still those three are well researched you will get in internet much literature, but lightning I think could have been covered, but due to a thing. So, except lightning others are some information you can get from internet also lightning need some theoretical understanding only electromagnetic understanding, but I am sorry I could not cover that in this class. Hope I have done I have presented something useful in this course. So, that later in your professional life you will be benefited as EMC engineer. Thank you.

MITIGATION OF ESD EMI

Spectral contents have sizable amplitude in GHz range

• Mitigation
  ➢ Put a metallic enclosure around the product
  ➢ ESD Current goes via neutral wire
  ➢ The voltage of the metallic enclosure may rise to several KV due to large inductance L. But no functional problem.
  ➢ However there will be penetrations. Hence, ESD mitigation is not simple.

Metallic enclosure

Neutral Wire