Electromagnetic Compatibility, EMC
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Module 6.2 Lightning Protection-Currents, charges and fields
Lightning and Electromagnetic Interference (Lightning Protection)

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Lightning and electromagnetic interference or lightning protection this is module number 6 point 2.

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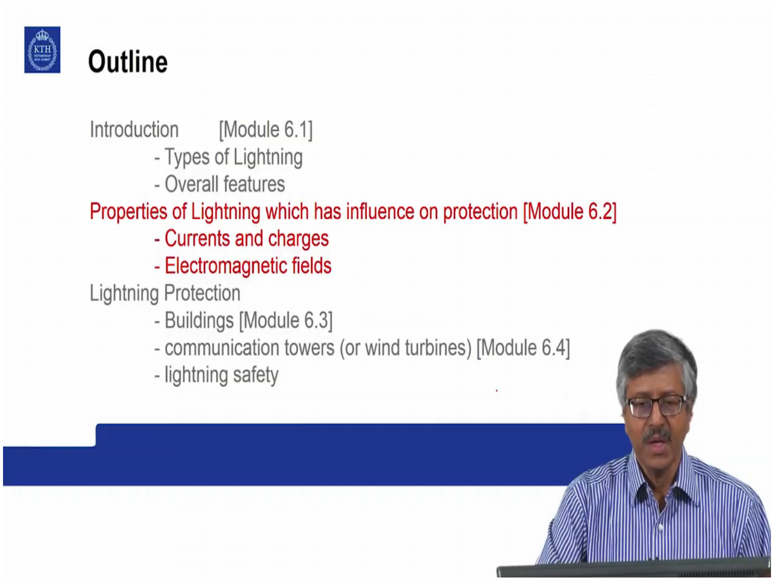

In this we will look at properties of lightning which has influence on protection. We will concentrate on currents and charges from lightning flash and the electromagnetic fields.

So these are the two quantities that affect the earth bound systems.

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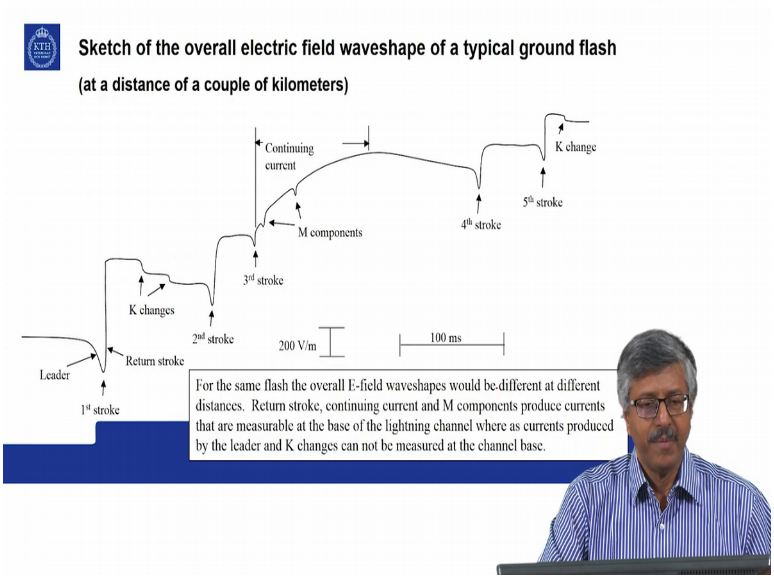

What is shown here is the overall sketch of vertical electric field wave shape of a typical ground flash at a distance of couple of kilometers.

So this is from the lightning channel. These fields are produced by the lightning channel, the vertical path from connecting earth to the cloud. Now if you look at the portion over here

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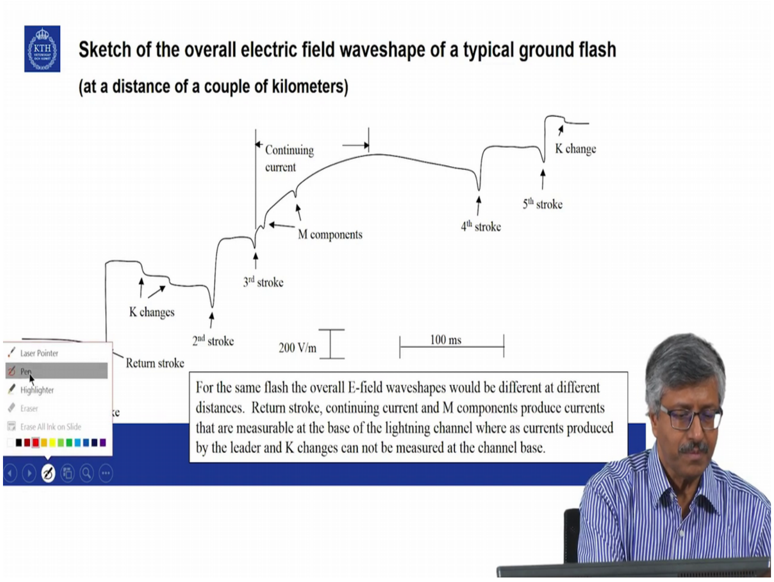

so as lightning is coming down from the sky, first it is in form of a leader. That you will not be able to see with the naked eye. As it is approaching the ground it will create the electric field change that goes in one particular direction.

So here

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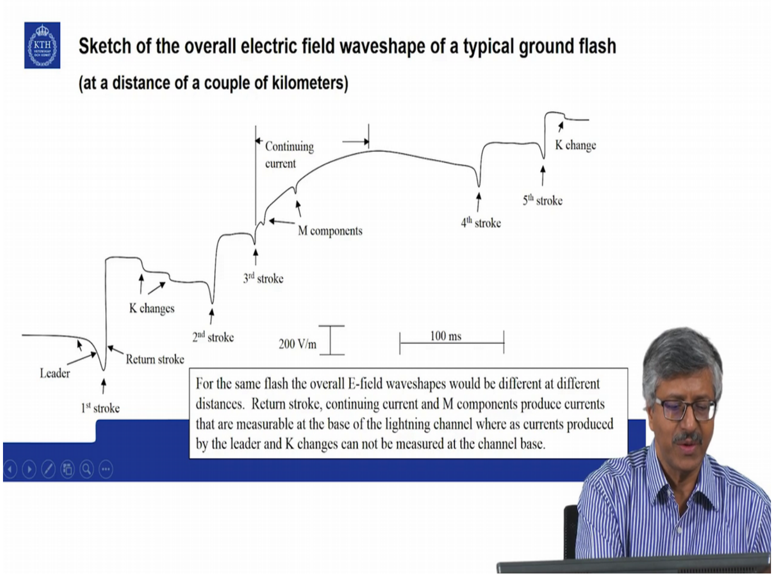

it is negative, this is a negative leader. So we are talking of negative cloud to ground flashes. Now the time scale is this much is about 100 milliseconds.

So we are talking of about several millisecond process. The speed of the leader may be of the order of 10 to the power of 5 to 10 to the power of 6 meters per second.

When once it comes very close to the ground there would be upward leaders going from objects from the ground which will connect with this downward leader

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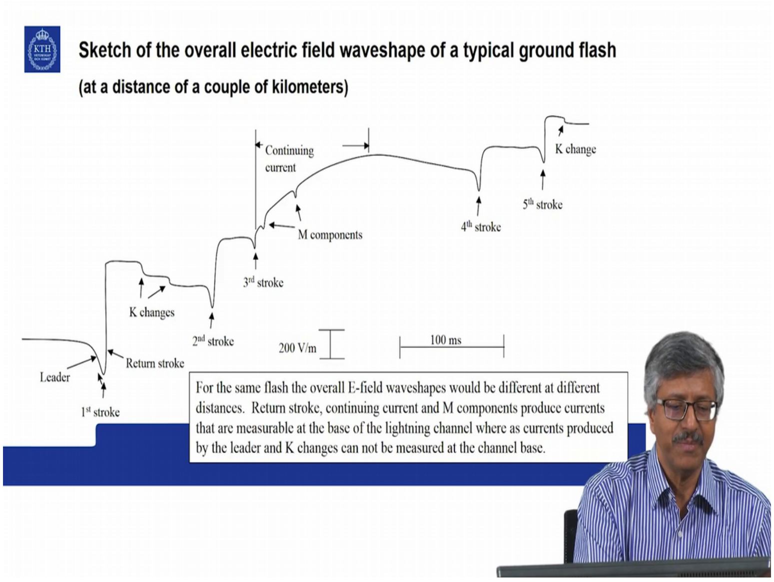

and you get their return stroke which is a very fast rising current associated with that, you hear the bright light and thunder.

So that process is shown over here

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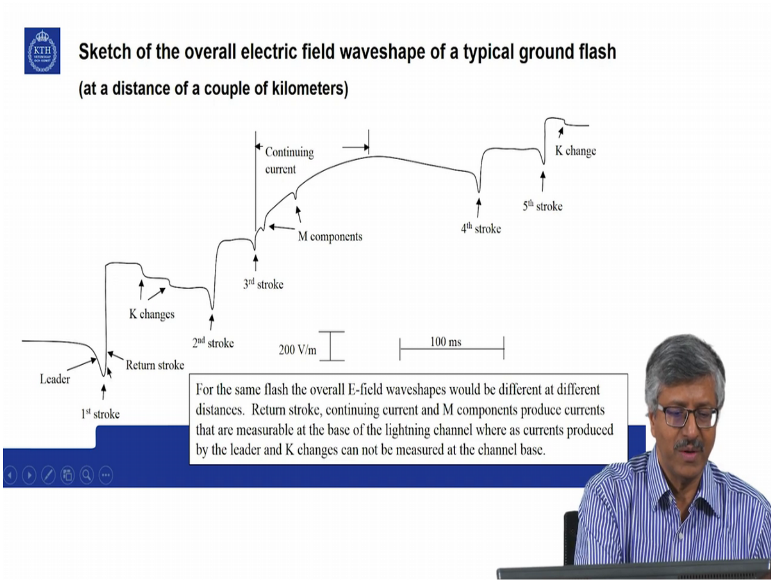

so this is how the electric field change will look like during a return stroke. So the rise time here is just a few microseconds only.

So from milliseconds scale, this process they are in microsecond scale. The vertical scale is around 200 volts per meter if you take this much distance

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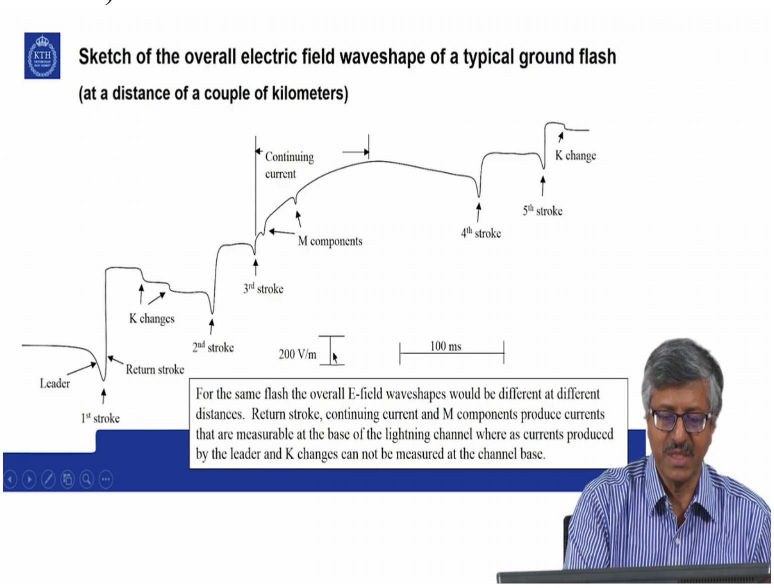

and this is couple of kilometer away from the channel.

And the return stroke returns the cloud and travels horizontally neutralizing several charges and the channel to the ground, you know become kind of extinguished in the sense that there may still be a plasma channel but you will not be able to see it.

It is not bright anymore. So it is a dark period and during that time there will be rearrangement of charges in the cloud that will manifest in the electric field as step-like changes and they are called K changes.

Then after that along the previous channel there may be another leader coming down and these leaders are called dark leaders or subsequently this. And again, I mean the second scale then as it is approaching the ground you will have another return stroke.

And that return stroke is shown here

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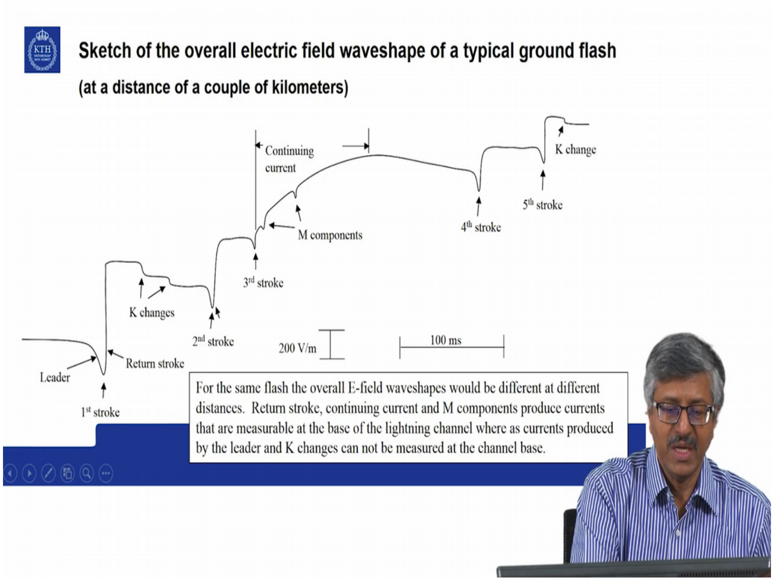

The second stroke in microsecond scale then after that again you have a dark period then along the channel the third stroke, well obviously this stroke

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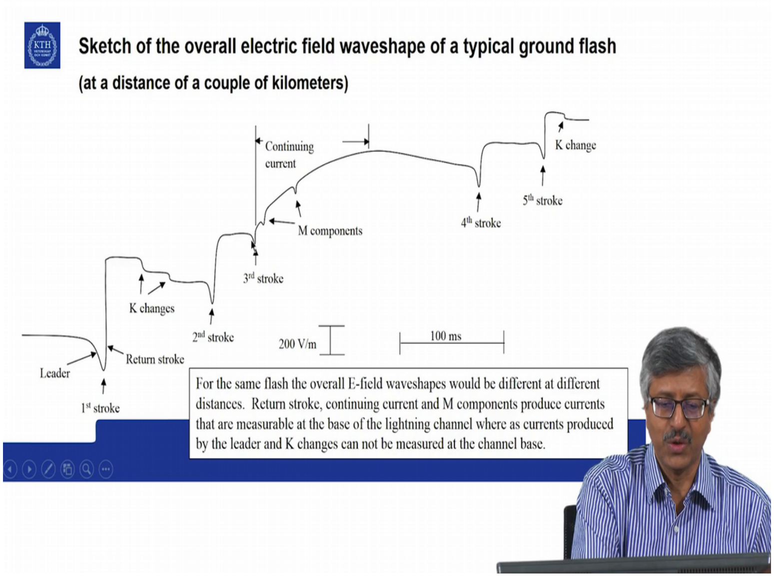

is very small stroke from the magnitude you can see.

Then following that, in this particular case you will see a continuous luminosity of the channel and that luminosities are presented in the electric field by a slowly varying electric field. So this is the continuing current phase.

It means that the return strokes are of the order of few thousands of amperes whereas during this continuous current which lasts several few hundred milli, up to few hundred milliseconds the currents are of the order of may be, you know less than 1000 ampere or few hundreds of ampere already.

And, but that will give a glow to the channel. And during that period you will have again several pulses coming down the same time which are called M components and that are shown here. These are not return stroke but slow-varying pulses.

Then you have a dark period over here

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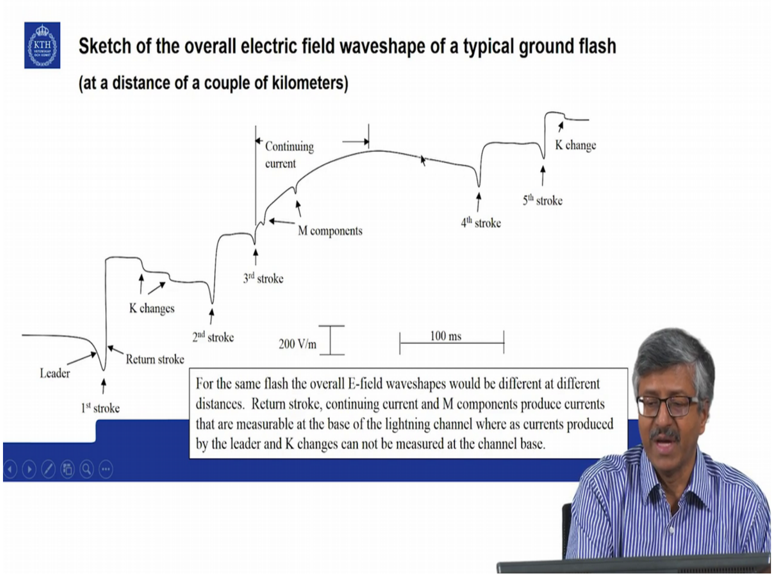

then again a fourth stroke then again a fifth stroke then some rearrangement of charges in the cloud then finally the flash gets extinguished. The whole process is less than 1 second.

So this is a pictorial

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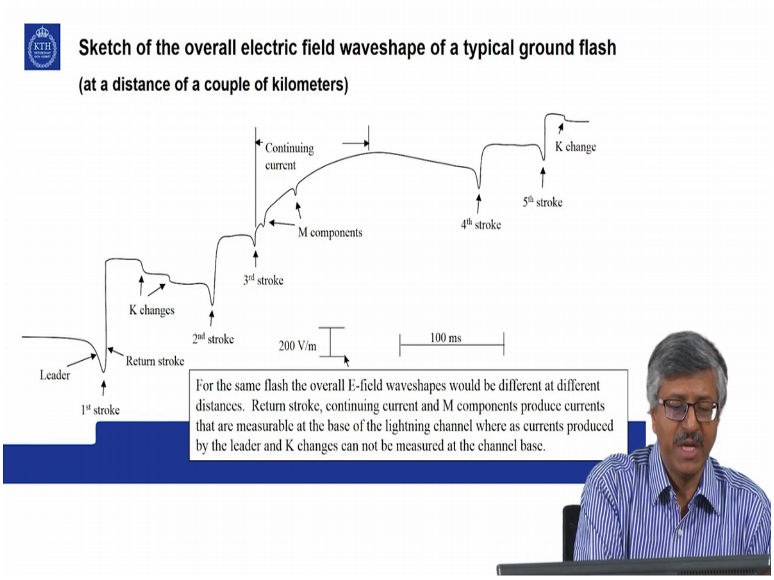

of a suggestion of an actually measured lightning flash in Florida in the 1970s.

So this gives several processes in the lightning flash and of that, as far as interaction this system on the grounds is concerned, we are mostly concerned about the return stroke, that is the most energetic thing and we are also concerned by this continuous current also.

Because even though it carries only hundreds of amperes, it, because of the long time it produces lot of charge. And we will see that lot of charge means fire hazard to the objects and other things.

So the return strokes and continuing current are most important as far as lightning protection is concerned. And the leaders are important because it is these leaders that will finally decide where the lightning will strike.

So there is a empirical formula between the charge in the leader as it is coming down and the peak current in the return stroke. So this peak current in the return stroke will decide how, at what distance the lightning will decide where it will strike.

Now so the last 40 or 50 meters or even 100 meter distance from the tip of the leader to the striking object is very crucial because it is during that time the upward leaders will be initiated from the grounded objects and it will be decided where the lightning will be striking. So this has got an influence in the protection also. We will see that in a later module.

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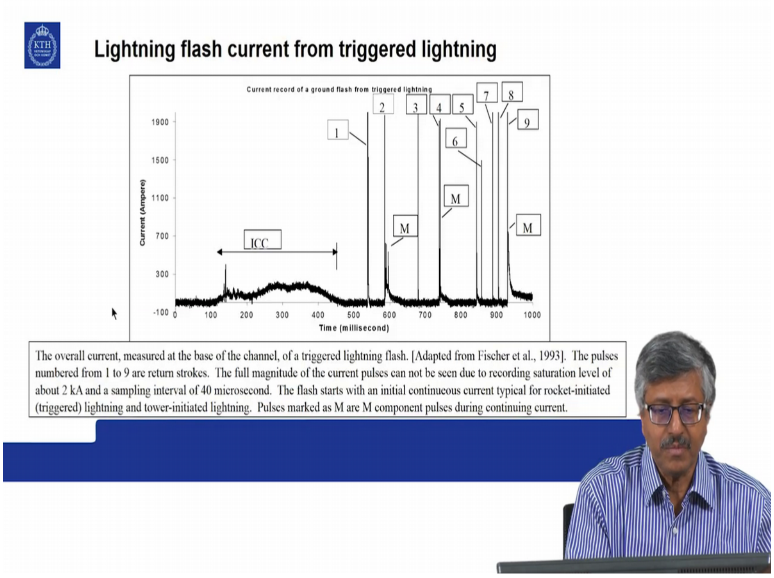

Previously we have seen the process of triggered lightning by shooting a small rocket upward with a trailing wire. And lightning can be artificially triggered with those type of technique from thunder clouds.

So what is shown here

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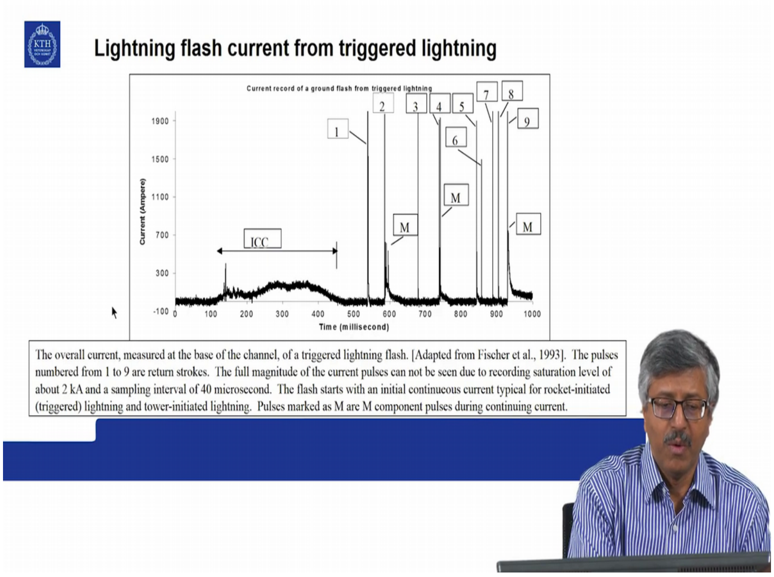

is a current that is measured at the base of the channel, actual lightning current during one of those trigger lightning.

And here if you look at this scale

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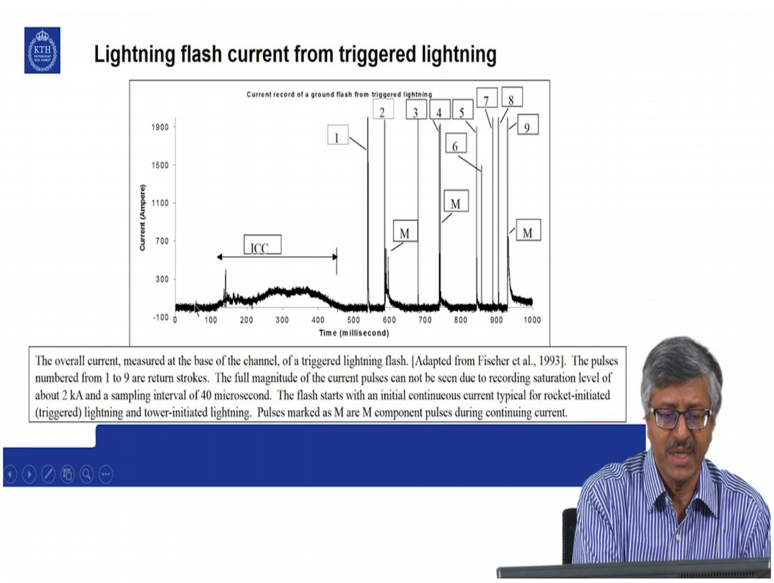

here it is in millisecond up to 1 second is shown, the current is in amperes, up to 2000 amperes are shown. Now these pulses 1, 2, 3, 4 like that most of them are above 2000 amperes but it is kind of cut, to show the finer details of low currents.

What you see here

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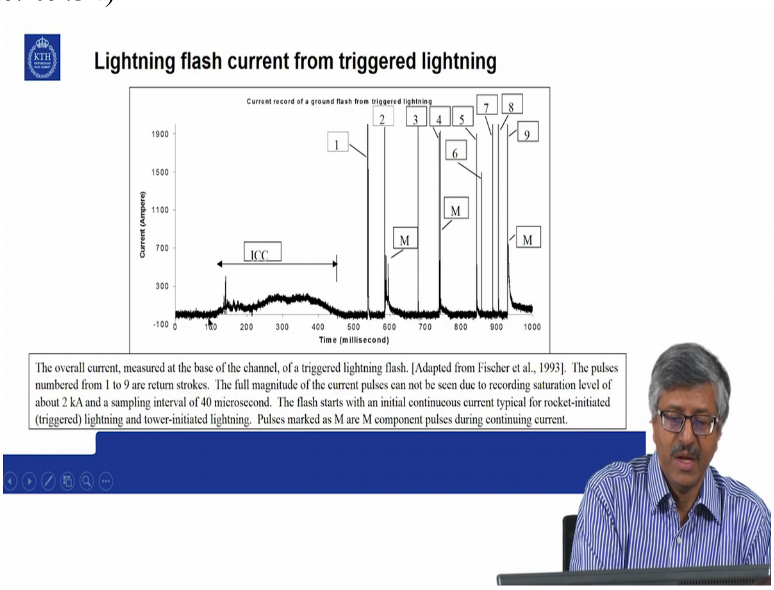

is the initial continuous current process of few hundreds of ampere in amplitude. This is the so-called stage immediately after the wire (()) (09:53) where there is a continuous current. This part is only present in upward initiated lightning or in triggered lightning.

It is not there in natural lightning. So your first stroke is kind of replaced by this initial continuous current. But remaining parts of lightning is very much similar to natural lightning. So first stroke, second stroke, third stroke so up to 9 strokes are there and you have some continuous current and time interval are several milliseconds and here this

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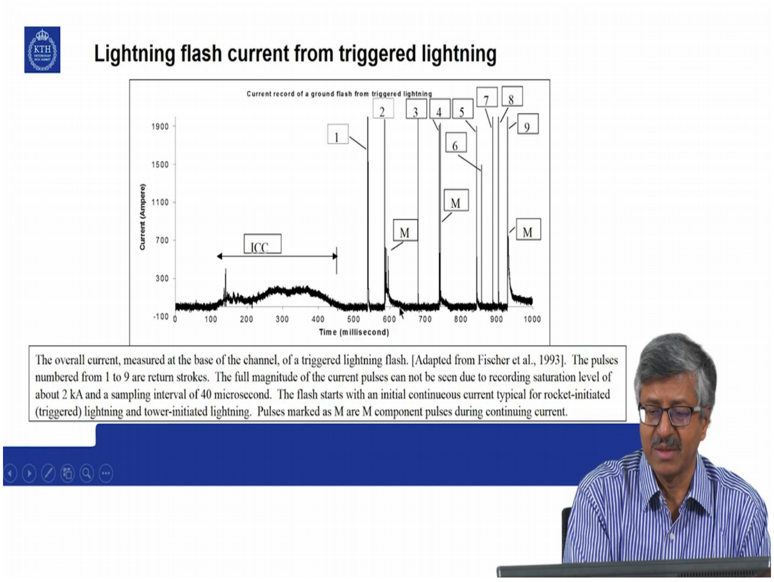

little more than 100 milliseconds and M components, this slow varying pulse superimposed on the continuous current.

So when an object is stuck by lightning then all this kind of environment is present. So the object is subjected to not just one lightning pulse but several pulses between the flash, separated by few tens to few hundreds of milliseconds. So that is the lightning strike environment.

And associated with that you will have strong electric and magnetic fields.

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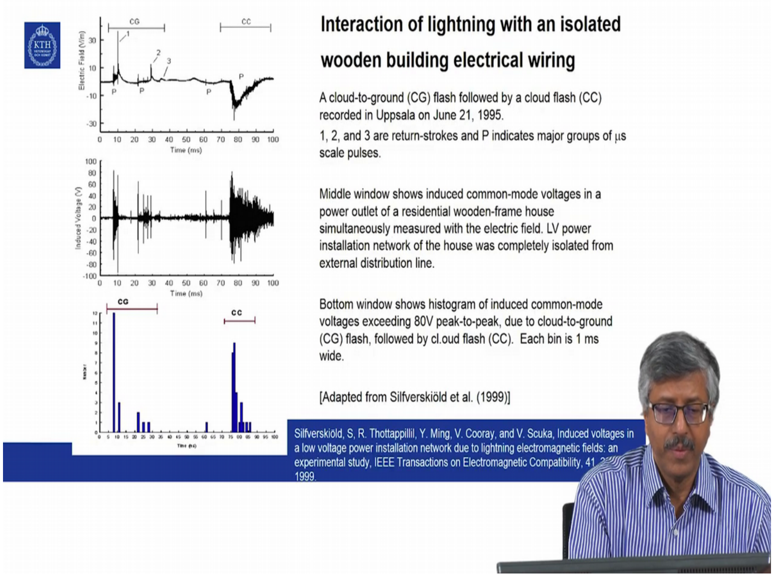

In this picture some measurements done in Uppsala in Sweden in 1995 are shown.

So the top picture shows overall wave-shape electric field change wave shape from lightning during a thunderstorm and the middle graph shows the current measured in the power outlet between one of the wires and the ground, the earth conductor.

So it is like a common mode current, common mode voltage, actually it is voltage, common mode voltage of a wooden building but it is completely isolated from external power lines. So it is like a huge object, a building with normal electrical wiring, piping and everything. So what is tried here is to see what effect lightning will have on a structure.

So the voltage is measured in one of the power outlets between one of the two lines and the earth. Now these are the actual voltages and this lightning was you know about 20 kilometer away. And first let us describe this electric field diagram.

So what is mentioned as P here are very narrow pulses that happens in the cloud. It has not happened in the ground. Or in the channel to the ground. So the leader is not yet initiated here. So these are just breakdown processes within the cloud that is, may be several tens of kilometers away from the building then already the building is responding to those events in the cloud.

So the structures can respond not only to the events that happens in the lightning flash channel to the ground but even those events that happens within the cloud, even before the channel is formed.

So you can see all these induced voltage pulses up to 80 volts and in this bottom graph how many pulses above certain value are counted, certain threshold value. So here bottom window shows histogram of induced common mode voltages exceeding 80 volt peak to peak, say for example this is 40 and this is 40 so 80 volt peak to peak, so how many pulses are exceeding that value?

So already at around 7 millisecond you have 12 pulses that exceed 80 volt peak to peak has occurred. So like ways you can follow how intensively induced voltages are there by, from this graph and this shows.3 the actual wave shape of the induced voltages on a millisecond scale.

For finding details one has to find it in a microsecond scale. And this is the first return stroke. Then after that again you have some quiet period and some events in the cloud and again the structure is responding to that producing pulses. Then the second return stroke, third return stroke, they are very small return strokes then some pulses in the cloud.

Then what is shown here

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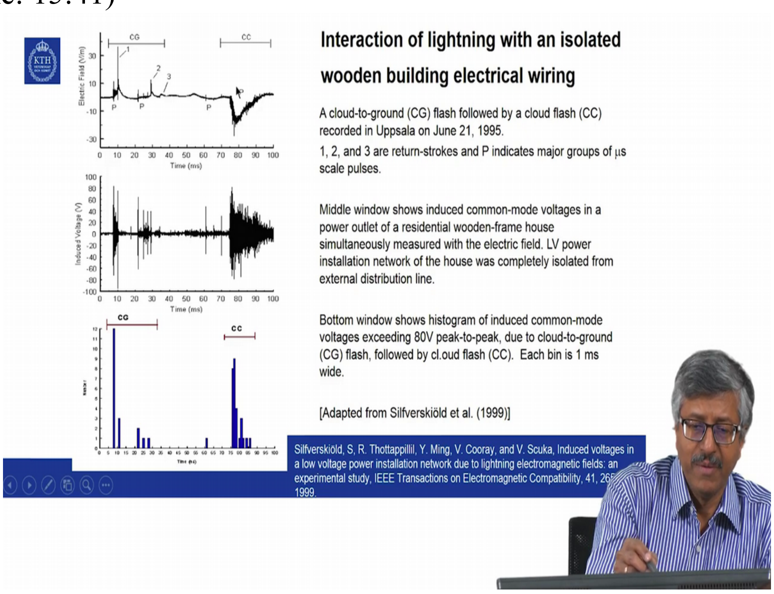

is a cloud flash. It has no connections to the ground. This happens in the cloud only. So what is interesting is that even though all these pulses, bipolar pulses are happening in the cloud, the structure is responding to this and you can find how many pulses exceeded 80 volt peak to peak over here

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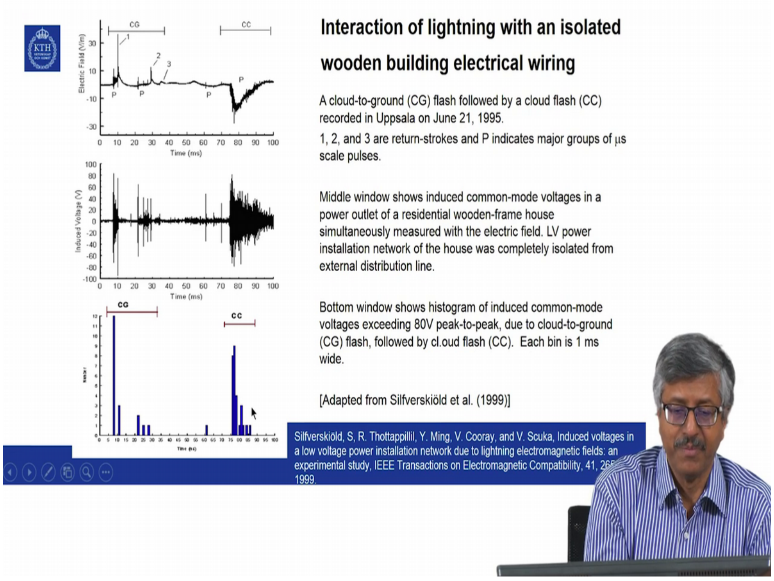

So the conclusion from this is that any lightning that happens, whether it is cloud to ground or cloud to cloud, you know the structure is responding. But usually it is cloud to ground lightning that is more of a threat because this is now more than 20 kilometer away.

But it can be just a few kilometer away from the structure. Then of course these peaks, return stroke peaks can be quite dominant in inducing the voltage in the structure and that will have extremely high values compared to that happens in the cloud.

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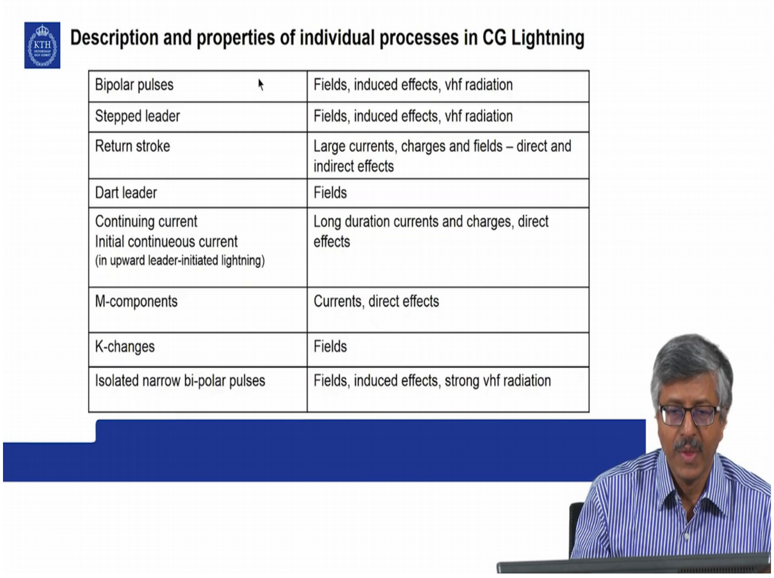

So if you look at the lightning flash there are many events that happens in a lightning flash and all of them has got some effects on the structures. For example we are not looking into the properties of all of these, we will only look at some properties of return stroke and continuing current only.

But there are many events in lightning flash that will produce electric and magnetic fields, induced voltage effects, V H F radiation etc whereas return stroke can directly strike objects and produce large currents charges, not only the fields. So this becomes most important for our study, the return strokes.

And M components also to some extent, because that also and continuing current and M components goes together. So this also can have direct effects. For other events it is mostly electromagnetic fields.

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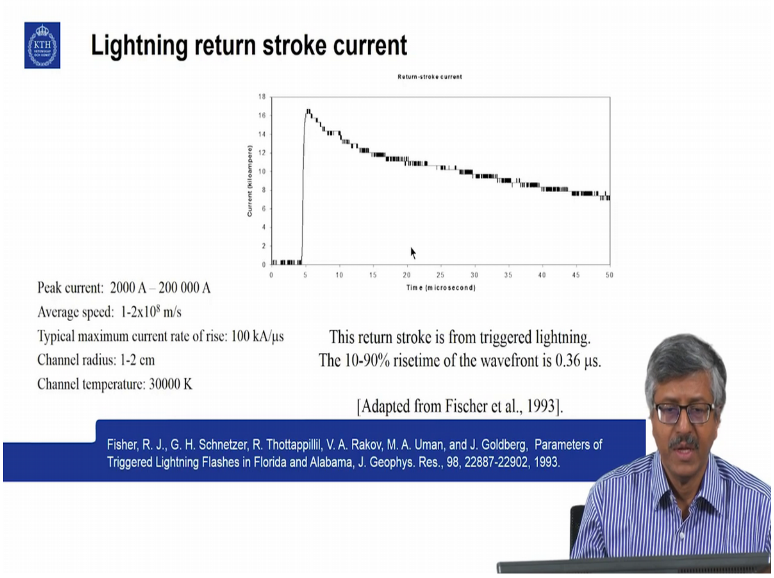

The waveform of a lightning return stroke current measured at the base of the channel is given. You know, from around one second this shows only 50 microseconds. So 1 by 50th of million you can say of length of a record.

And in this particular return stroke

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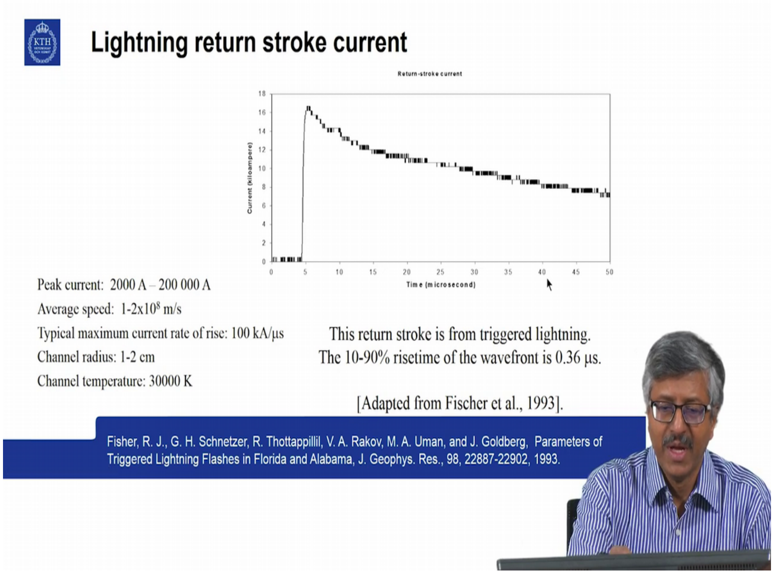

it has got 16 kilo amperes, 16000 ampere peak current and 10 to 90 percent rise time, that is from 10 percent of peak value to 90 percent of the peak value, it will be point 3 6 microsecond. So 10 percent and 90 percent are taken to remove some of the uncertainty at these junctions.

And the range of peak currents for return strokes are anywhere from 2 kilo ampere to 200 kilo ampere and average speed of the return stroke pulse propagation from ground to cloud is 1 to 2 into 10 to the power of 8 meter per second, so one third to two third the speed of light. And typical maximum rate of rise is 100 kilo ampere per microsecond.

So we are interested, very much interested in this figure, in terms of peak current because current squared time in resistance you know you get, you know the total, the effect that is happening in terms of the power and here d I by d t.

Of course we can translate it into induced voltages in relation to inductance and this is the channel radius and channel temperature

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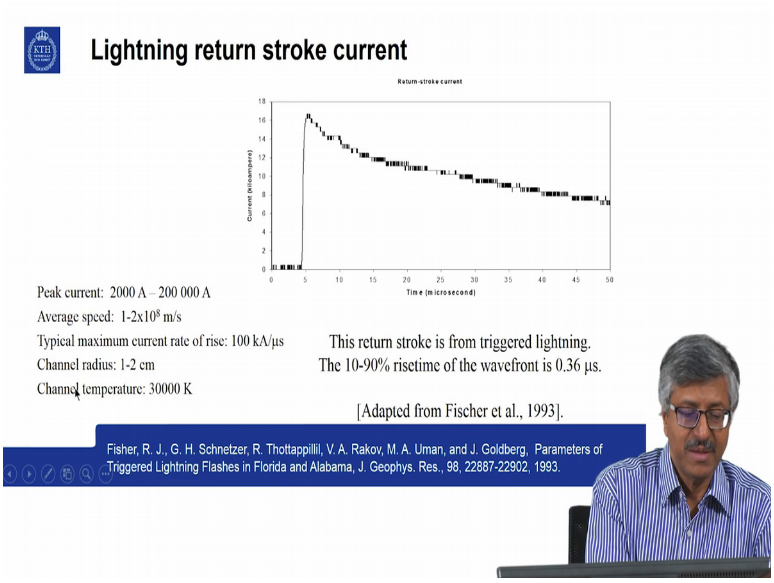

Of course this is important in terms of melting of the object where lightning is striking.

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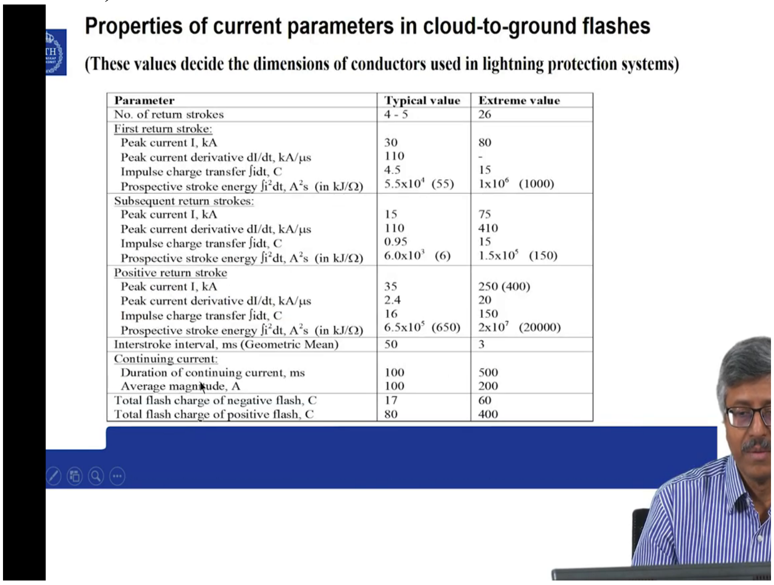

Parameter	Typical value	Extreme value
No. of return strokes	4 - 5	26
First return stroke:		
Peak current I, kA	30	80
Peak current derivative dI/dt, kA/μs	110	-
Impulse charge transfer ∫idt, C	4.5	15
Prospective stroke energy $\int i^2dt$, A^2s (in kJ/Ω)	$5.5x10^4$ (55)	$1x10^6$ (1000)
Subsequent return strokes:		
Peak current I, kA	15	75
Peak current derivative dI/dt, kA/μs	110	410
Impulse charge transfer ∫idt, C	0.95	15
Prospective stroke energy $\int i^2dt$, A^2s (in kJ/Ω)	$6.0x10^3$ (6)	$1.5x10^5$ (150)
Positive return stroke		
Peak current I, kA	35	250 (400)
Peak current derivative dI/dt, kA/μs	2.4	20
Impulse charge transfer ∫idt, C	16	150
Prospective stroke energy $\int i^2dt$, A^2s (in kJ/Ω)	$6.5x10^5$ (650)	$2x10^7$ (20000)
Interstroke interval, ms (Geometric Mean)	50	3
Continuing current:		
Duration of continuing current, ms	100	500
Average magnitude, A	100	200
Total flash charge of negative flash, C	17	60
Total flash charge of positive flash, C	80	400

So the properties of current parameters in cloud to ground lightning is summarized here. So you can use this for reference. What is shown here is the typical value or some sort of an average value and what is shown here is extreme value that is maximum value that people have measured with real lightning.

For example number of return stroke in a flash, typically a flash contains several return strokes. So typically it is 4 to 5 whereas extreme value can be 26. Peak current in negative tropical lightning, then peak current derivatives, impulse charge transfer that is during the return stroke how much charge.

If you integrate the waveform of the return stroke, say for example you are, this is the return stroke So if you integrate this area, so this is in time and this is in ampere.

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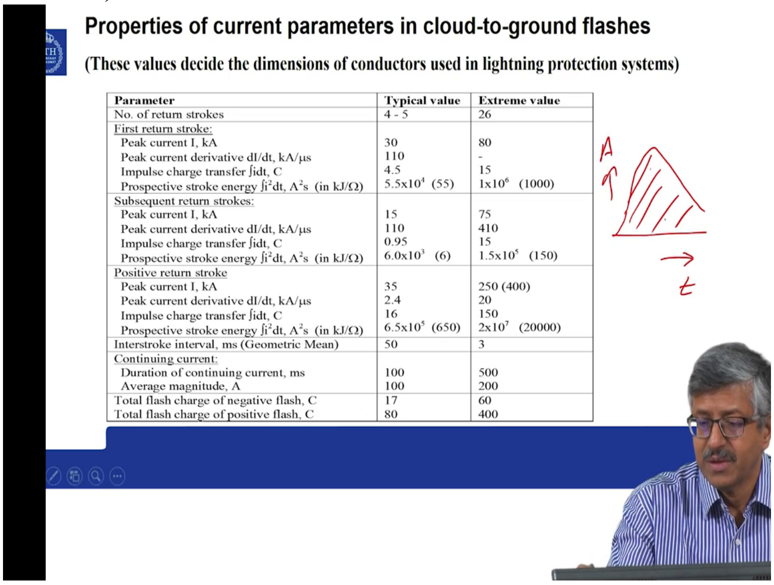

So if you integrate this area that will give you the charge. So impulse charge and prospective stroke energy, so if you take i square in each of these area, i squared,

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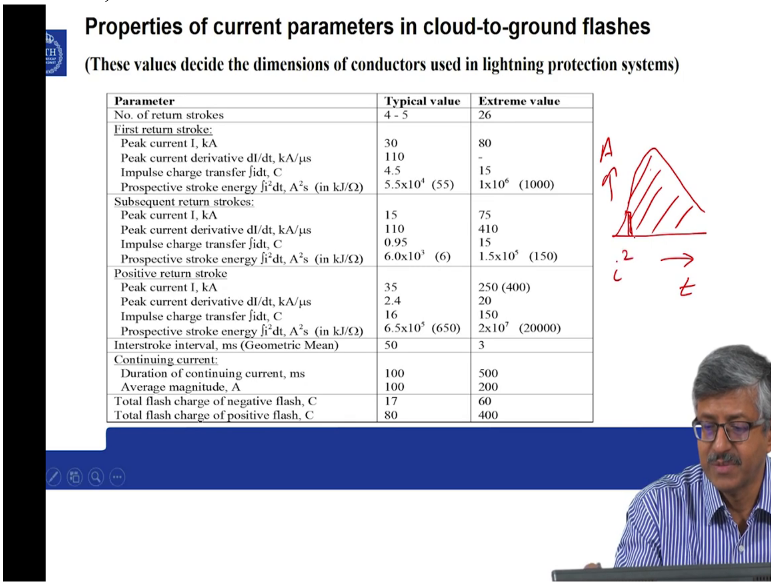

charge squared I mean current squared then delta t then if you sum up all those things then you get prospective stroke energy.

So this is for the first return stroke, this is for the subsequent return stroke that follows the first return stroke, so which are a little lesser in value, then positive return stroke, this is from positive cloud to ground lightning where you have much more higher amplitudes in the extreme phases, then continuous current and total flash charge.

So these are important engineering parameters that are required in designing lightning protection systems.

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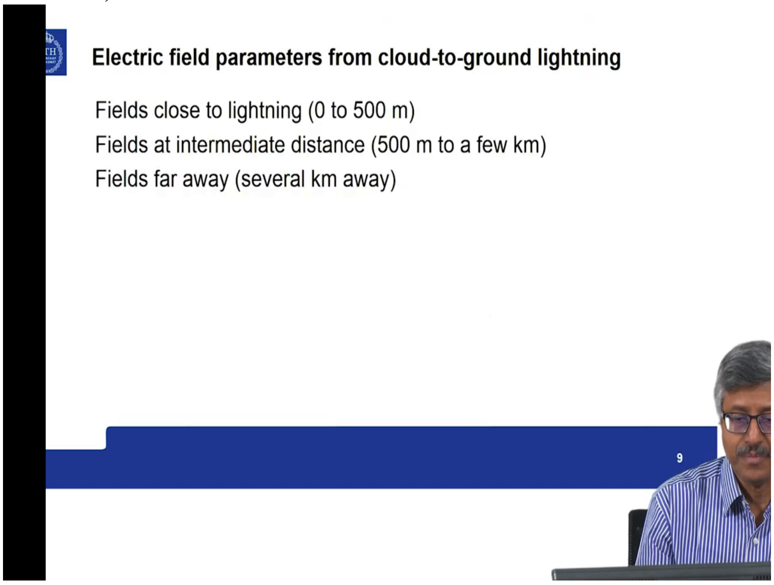

Electric field parameters from cloud to ground lightning, so fields, we will consider 3 distances. One is fields close to lightning; 0 to 500 meters let us say, that is half a kilometer. Then fields far away that is several kilometers away then some intermediate distance, 500 meters to few kilometer.

The reason for doing is that if you have the lightning channel here. And if you look at the fields, if you measure the fields at various distances,

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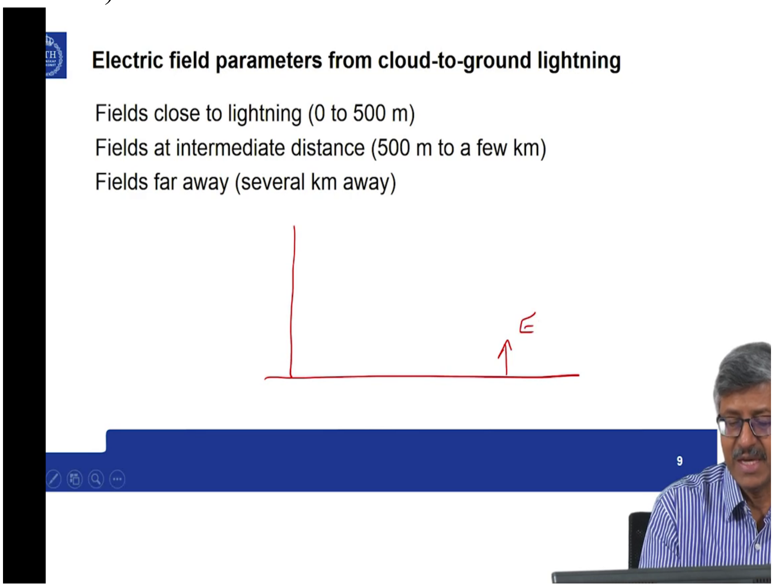

the vertical fields E it follows a certain relationship as a function of distance d.

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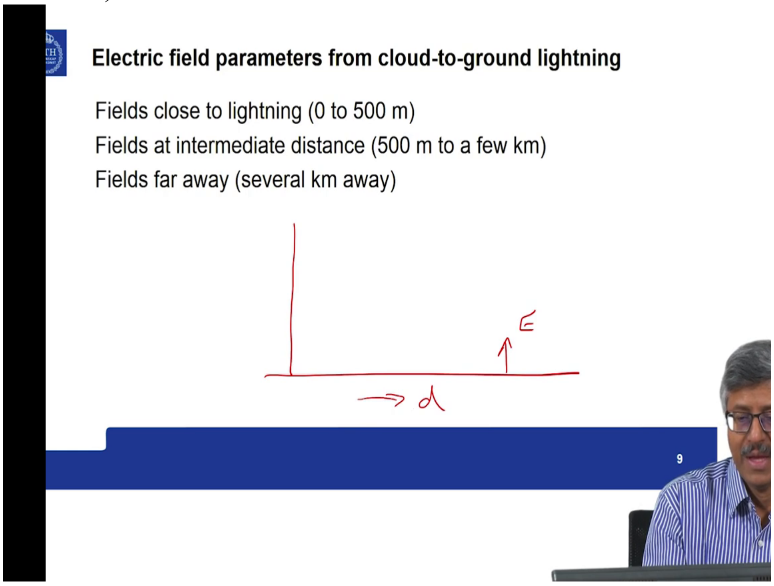

And close to the channel and faraway channel E is proportional to 1 over d,

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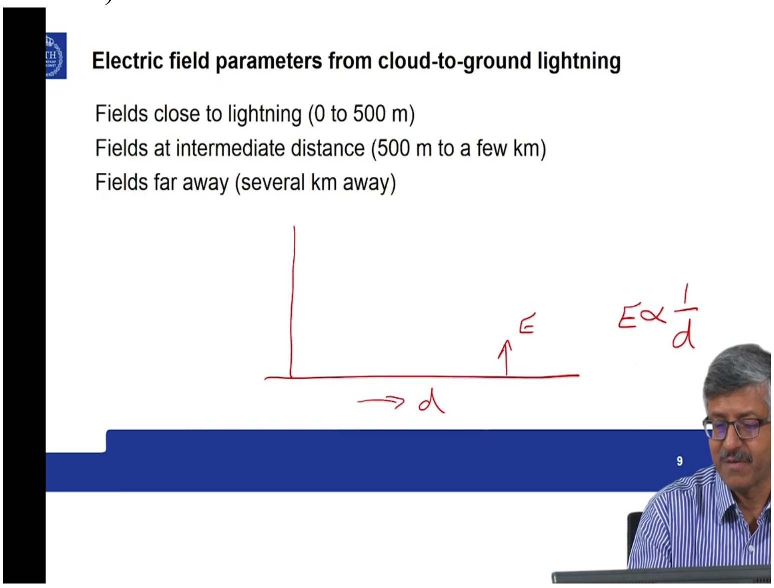

peak field; E p is proportional to 1 over d.

So here you can say that E peak is proportional to 1 over d, approximately

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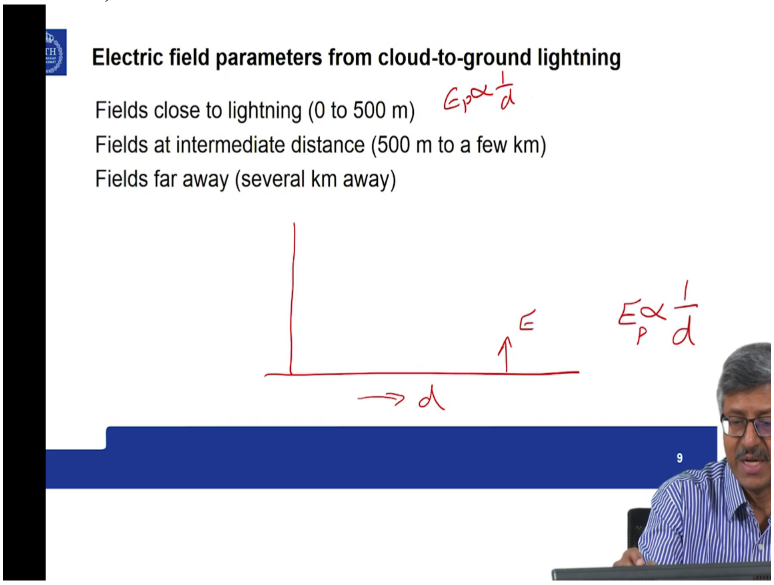

and here also E p is proportional to 1 over d.

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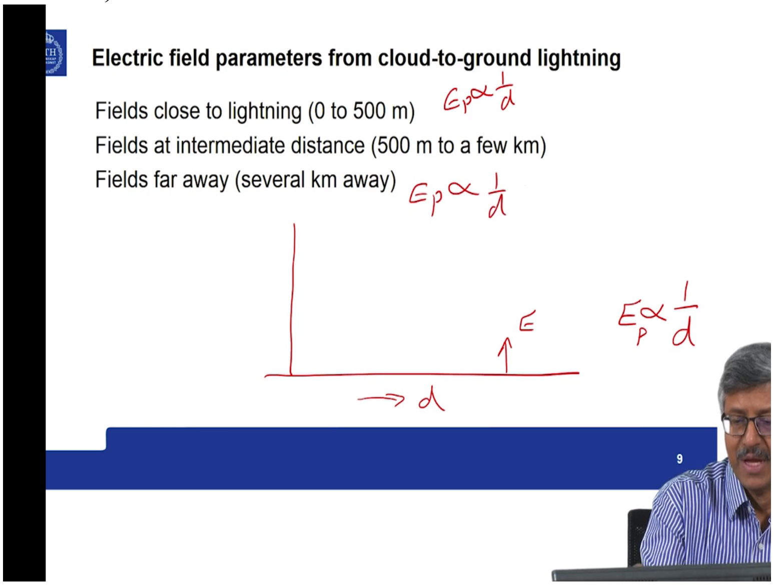

But here it is not

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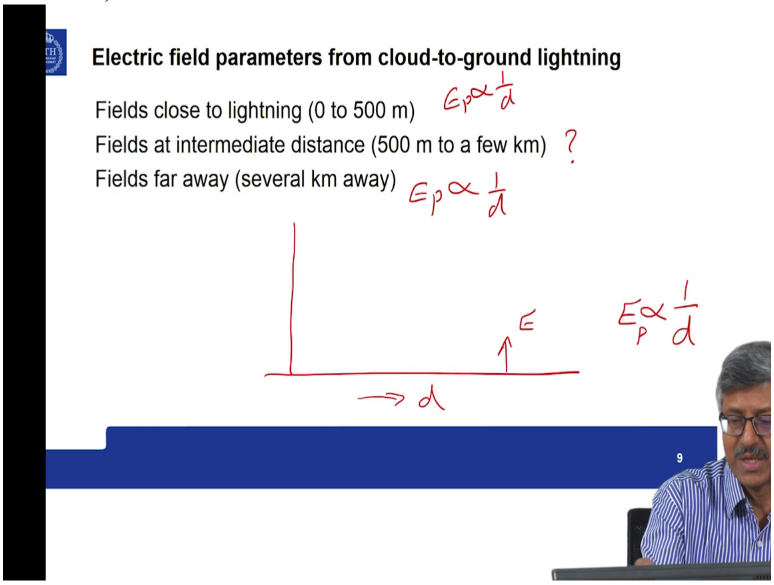

like that, in the immediate distance. That come from the peculiar combination of the geometry and the various processes and the channel that give rise to the field.

So let us look at the details.

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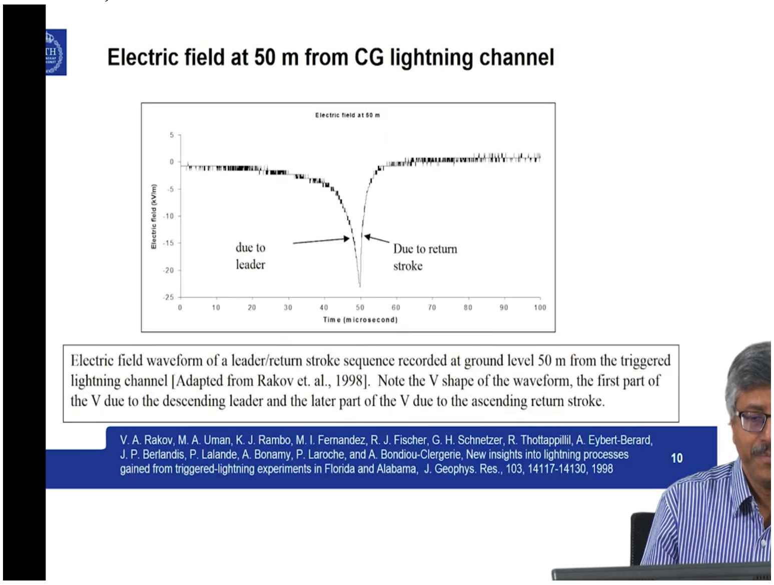

Electric field very close to the lightning channel, a picture is shown here. So you have the leader that is coming down. And now here this is in microsecond scale. Because you are so close to the channel, it is only a distance of 50 meter so this is the last several meters that you are seeing. Then you have the return stroke.

So this follows a very narrow bipolar pulse. This wave shape is also very different. Say up to 0 to 500 meter often you have leader and return stroke of this form this is the leader. And this is return stroke

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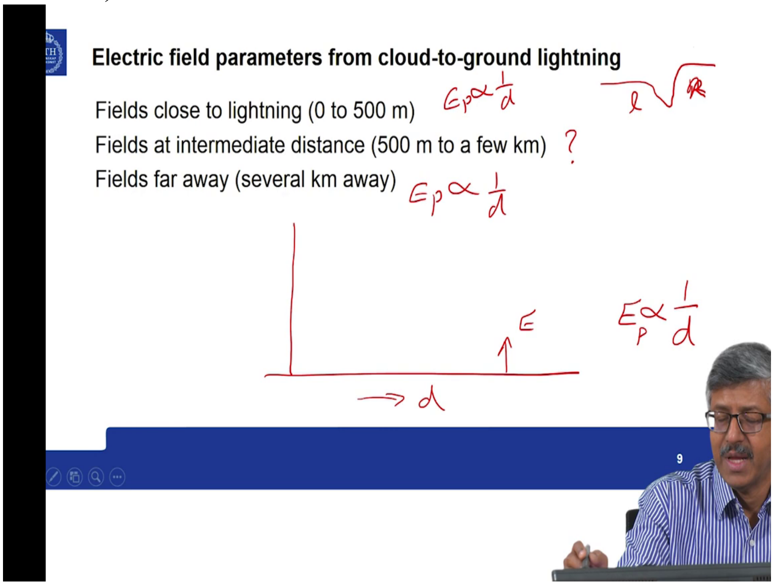

whereas in the immediate distance it may be something like this

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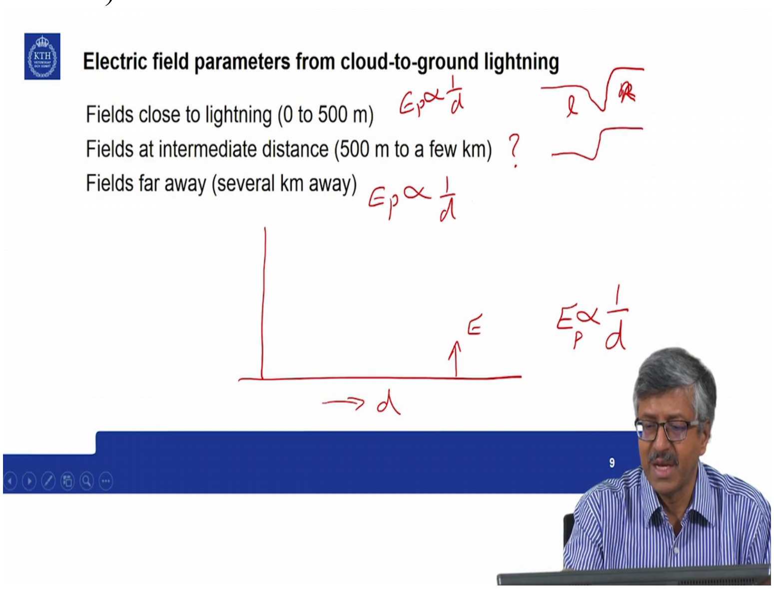

and far distance you will find only something like this.

So this is a return stroke and this is the leader,

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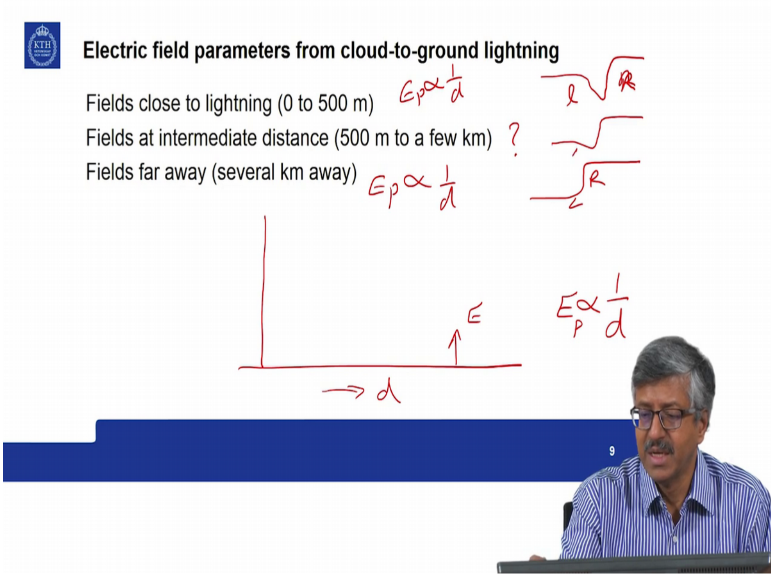

leader, return stroke. So even the wave shapes are different. So we are mostly interested in this return stroke part.

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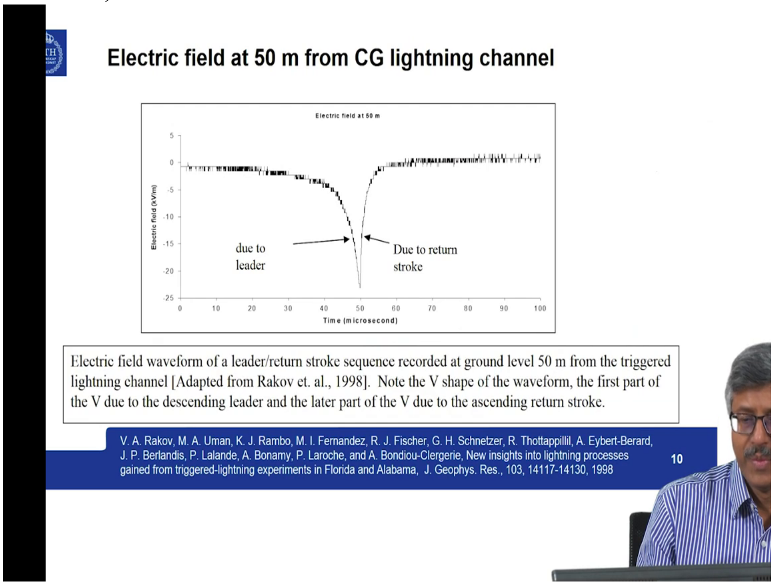

So this narrow bipolar, narrow bidirectional or narrow pulse is formed only when you are very close to the lightning.

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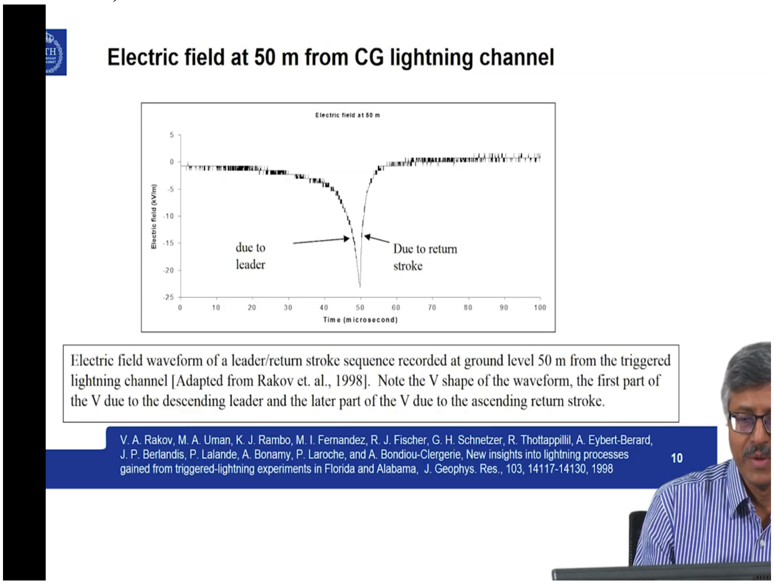

So even before the lightning is striking your structure will start responding to the leader fields.

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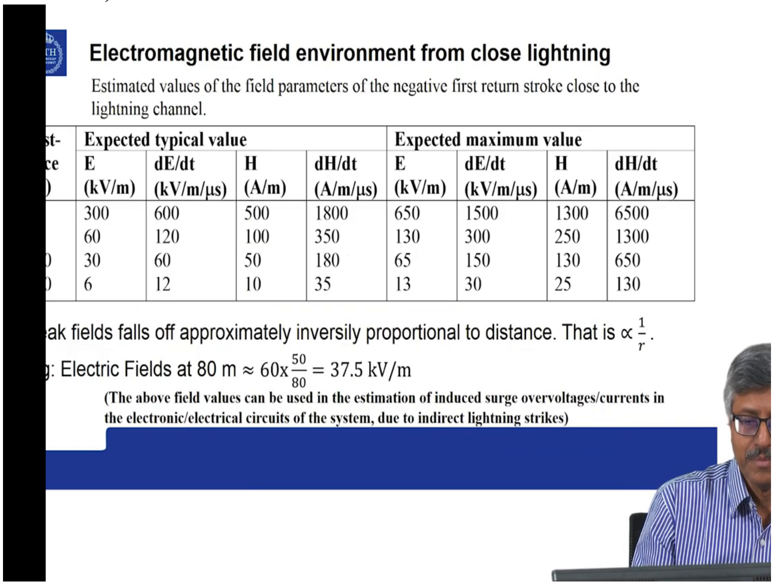

Now the electromagnetic field environment from close lightning are described here. E, d E by d t, H d H by d t, the typical values and expected maximum values are given, and at various distances from 10, 50, 100, 500.

So these are based on measured data and extrapolation of measured data is done here. So for example at 50 to 100 you have around 30, 60, 50 like that. So peak fields are also approximately inversely proportional to distance, that is peak field is proportional to 1 over r where r is the distance.

Say for example electric field at 80 meter then you will determine like, you have it at 50 meter, 60 so 60 into 50 by 80 because of this proportion so 37 point 5 k V per meter. So likewise you can determine the field peaks. And this is approximate.

Each lightning is different. The above field values can be used in the estimation of induced surge or voltage currents in electric, electronic, electrical circuits of the system due to indirect lightning strikes.

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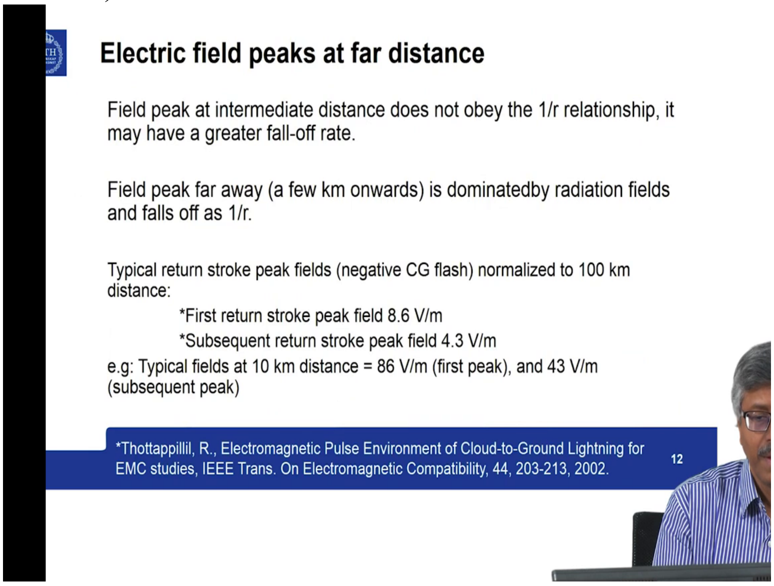

Now electric field peaks at far distance. Field peaks at intermediate distance does not obey the 1 by r relationship and it may have a greater falloff rate where as field peak faraway is dominated by radiation fields and falls off as 1 over r.

Now typical return stroke field peaks in negative cloud to ground flash normalize to 100 kilometer distance. For the first return stroke peak field it is given by the value 8 point 6 volts per meter or around that value and for subsequent return stroke peak it is around half that value for point 3 volts per meter.

Say since it obey roughly 1 over r relationship faraway, say typical fields at 10 kilometers distance you can find it to be 86 volts per meter first peak and 43 volts per meter subsequent peak.

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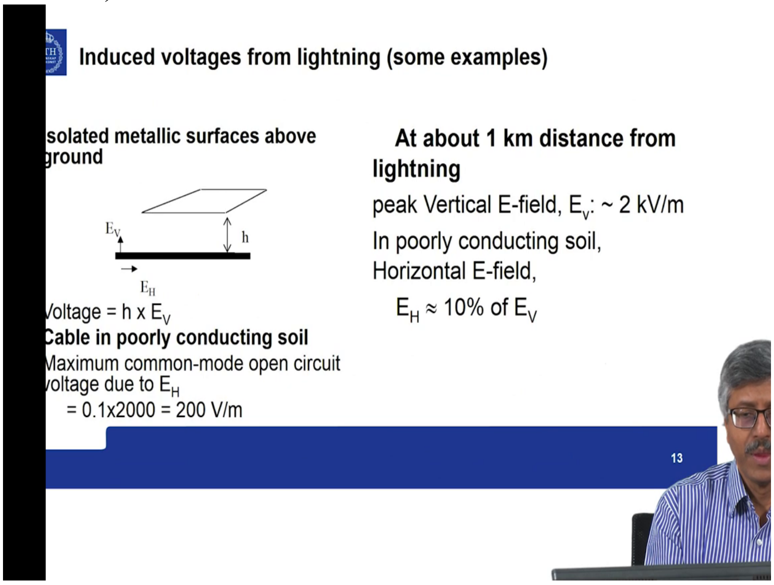

Now what are the effects of lightning electric fields and magnetic fields?

Say electric fields are vertical. So it means that electric field times distance will you give the volt. So if you have a metallic structure that is above the ground the structure will go up in potential by an amount of h times E v. So this is one kind of an effect.

So if you have different structures so these different structures may be at different potential depending upon the height above the ground, at about 1 kilometer distance from lightning let us say peak vertical field is 2 k V per meter then you can see that if height is h then you get, if it is 1 meter distance then you get 2 k V voltage, this vertical voltage.

Now if it is a perfectly conducting plane, there is only vertical field. But due to the poor conductivity in soil there will be horizontal component of the field also and that field is approximately 10 percent of the vertical field.

So if you have a cable that is being laid so you have a voltage, so this is your cable. And this is your E h.

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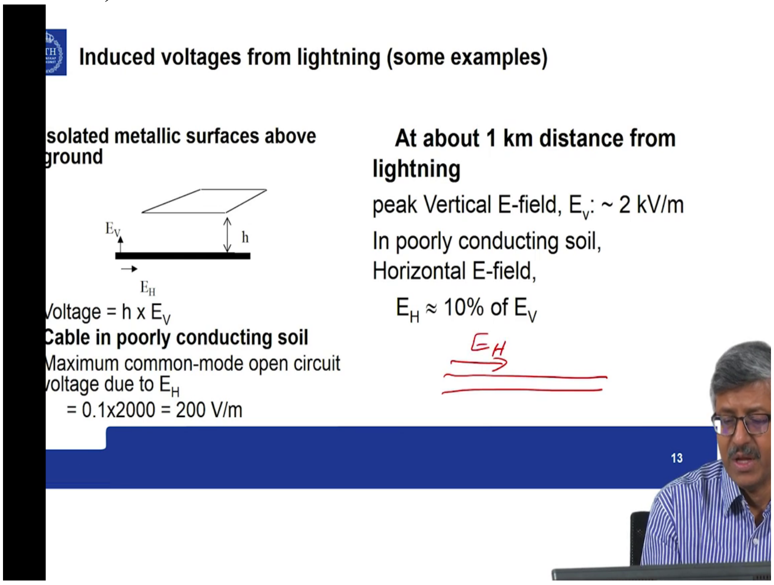

So if you travel certain distance then the voltage that will be produced, the upper circuit voltage that will be created will be this field times, you know the length of

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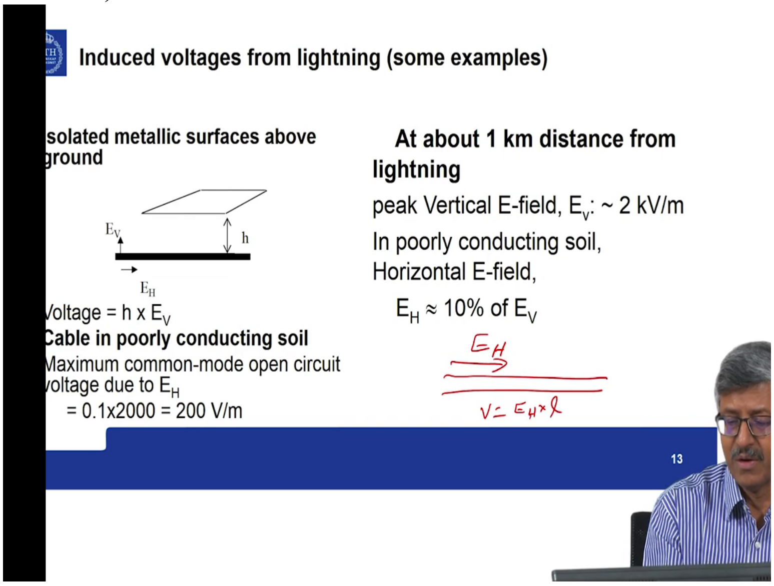

the cable.

So around 200 volts per meter can be produced on the shield as an open circuit voltage due to this vertical field from lightning.

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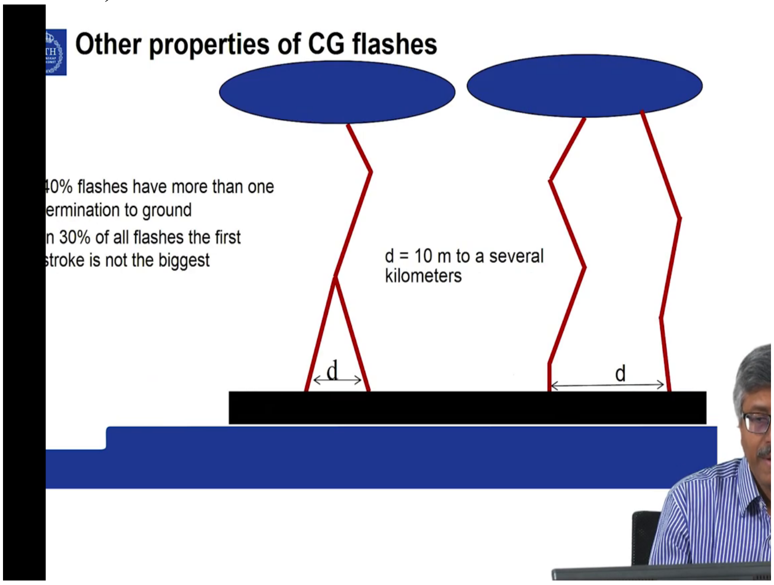

Now another property you have to be aware in lightning is that around 40 percent of flashes have more than 1 termination to ground.

So this can be within the same flash. So it can be that, one particular stroke has happened here. Then after, say several tens of millisecond, the second stroke can follow partly the same channel but then it can take a different termination.

So it is as if that, Ok lightning has struck one part of a building then second stroke may strike within tens of millisecond another part of the building. So it is a very complex kind of environment. And the distance d is from 10 meters to several kilometers.

So sometimes even from the base of the channel you will see totally two separate channels to the ground. And another interesting phenomena is that around 30 percent of all flashes, the first stroke is not the biggest.

So usually the first stroke is the biggest but in about one third of the flashes perhaps the second stroke is larger than the first stroke. Or the third stroke is larger than the first stroke. Even though on an average the first stroke is the biggest.

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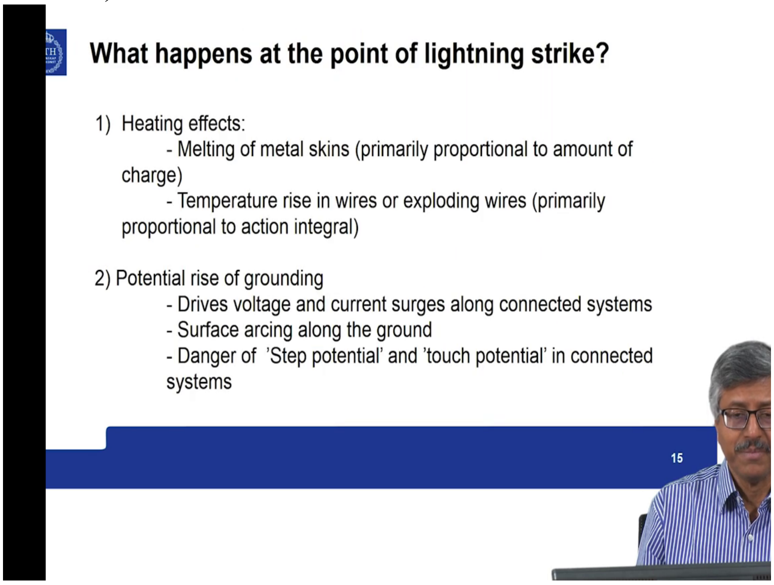

So what happens at the point of lightning strike? So one is the heating effect. Now because of the large currents and temperature.

So melting of the metal skins which is primarily proportional to the amount of charge that is involved, that is integral of the current over time and temperature rise in wires or exploding wires, this is primarily proportional to the action integral that is integral of I squared d t.

So it is as if, if that is if a wire is subjected to that current then depending upon the distance of the wire, the wire will be heated up. So this is the potential prospective energy that is available.

Then potential rise of grounding. So since there is large currents and voltages involved, the striking point will rise in potential and this drives voltage and current surges along any connected system to the other systems.

So due to that there can be surface arcing along the ground you have danger of step potential and touch potential in connected system. We will describe what is meant by step potential and touch potential.

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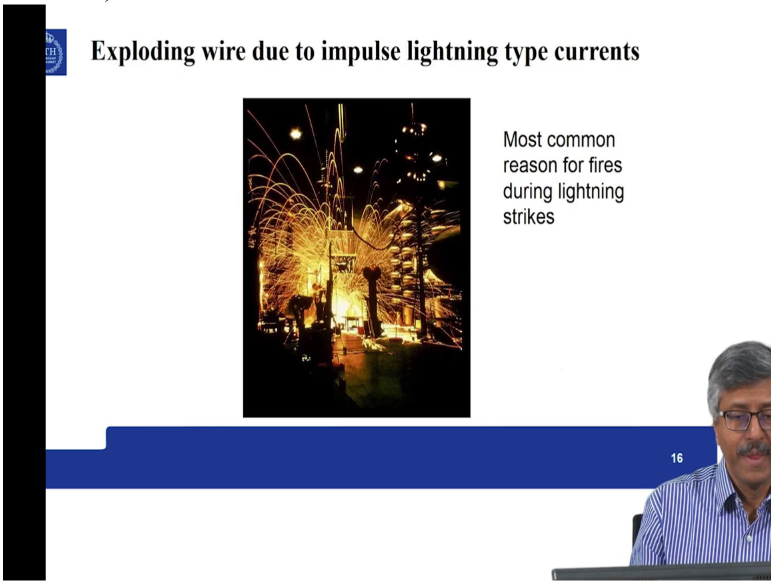

First of all, the exploding wires due to impulse lightning type of currents because of the enormous energy the wires may explode. This is an experiment from a high voltage lab of wire exploding when you subject it to lightning type of currents.

Often most of the reason for fires during lightning strikes are these type of exploding wires, when it gets into electrical wiring, antenna, TV antenna wires etc. It may explode and cause fires.

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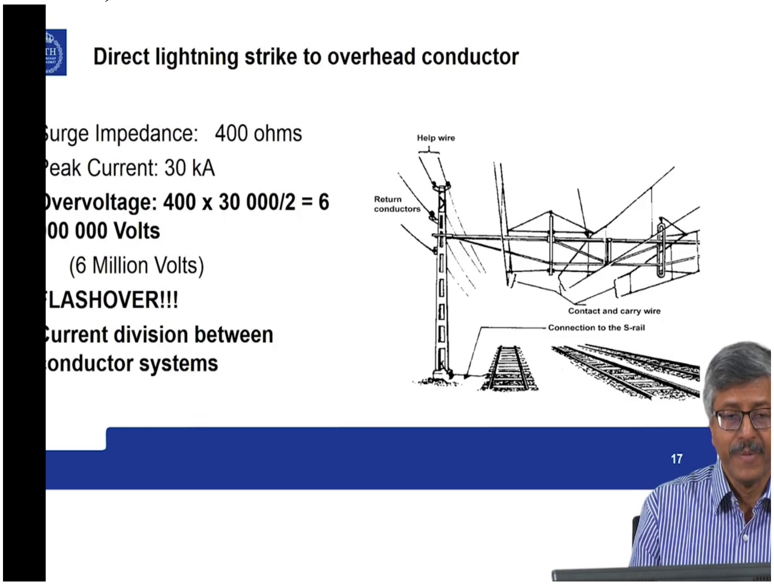

And does lightning strike to overhead conductor? Suppose, so this is a railway line. These lines may have surge impedance of the order of 400 ohms. Assume that your lightning has a peak current of 30 kilo ampere, the average current.

Then when it is striking the line the prospective voltage would be 400 ohms times the current, current times, impedance times the current. So the current wave may be divided into 2 part on both directions so we divide by 2.

So it can reach up to 6 million volt. But of course it will not reach up to, I mean before that if it will start FLASHOVER. So you will never measure 6 million volt because it is already flashing over.

And there is will be current division between different conductor systems. So lightning currents can get into here. It goes, flashes over to the other wires, all of the place it will be going.

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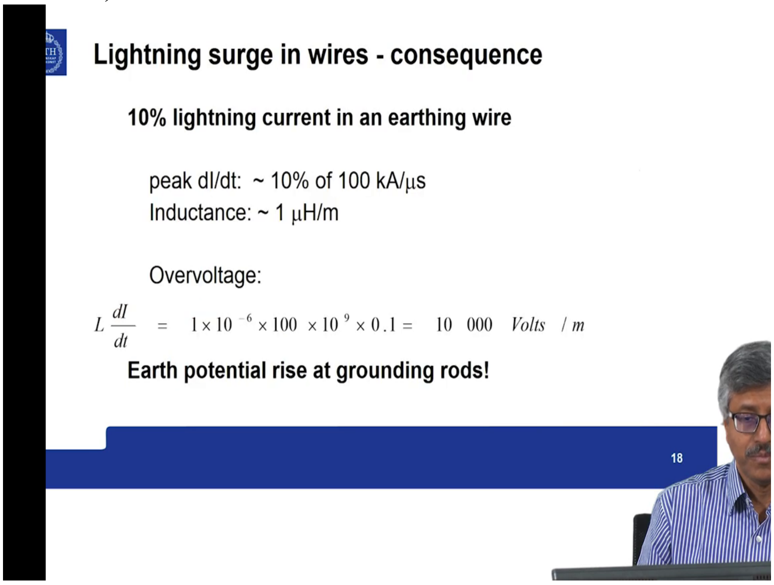

Like in surging wires, the consequence, even if 10 percent of the lightning current is in the earthing wire, let us say peak d I by d t is 10 percent of 100 kilo ampere per microsecond, and inductance is 1 micro Henry per meter, over voltage produced will be L d I by d t.

It will be around 10000 volts per meter. So suppose you have a lightning strike to, even 10 percent of lighting current is carried by a big generator set or something like that.

In its earthing wire it can have 10000 volts per meter of the wire compared to the ground. So earth potential rise at grounding rods, so this can be even at the lightning grounding rod, so it will tend to drive currents readily away from them to all connected systems.

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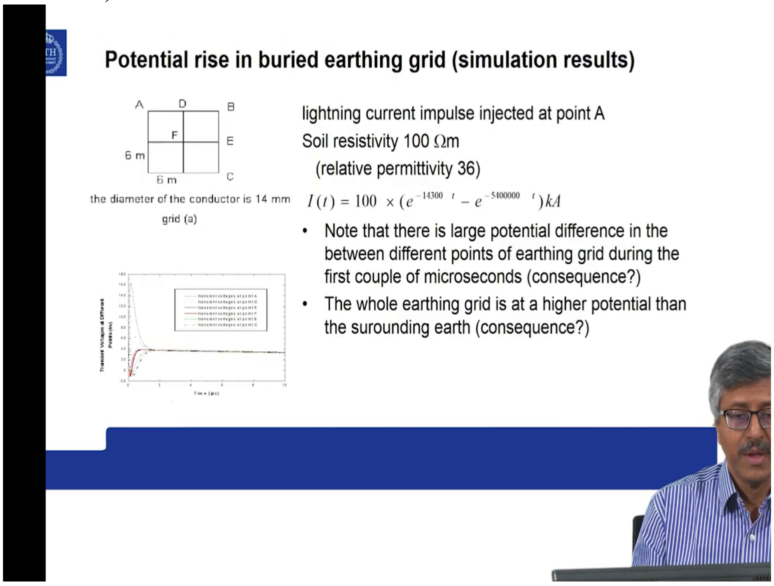

So this phenomena can be illustrated by a simulation. So typically in substations, power substations. We have substation mat in the form of a grid underneath the substation buried so that the 50 Hertz power supply.

I mean it is kind of a equipotential grid so that you do not have any big potential difference between different parts of the substation under 50 Hertz even if there is large current flow through different wires.

And, but is this enough during the lightning strike? But during the lightning strike this will not remain at equipotential. That is shown here using a simulation. Soil resistivity is 100 ohms per, 100 ohms meter or you can represent it as 1 by 100 ohm meter or point 0 1.

So this is equal to 0 point 0 1 Siemens per meter in conductivity. So this is resistivity, this is conductivity so this is conductivity.

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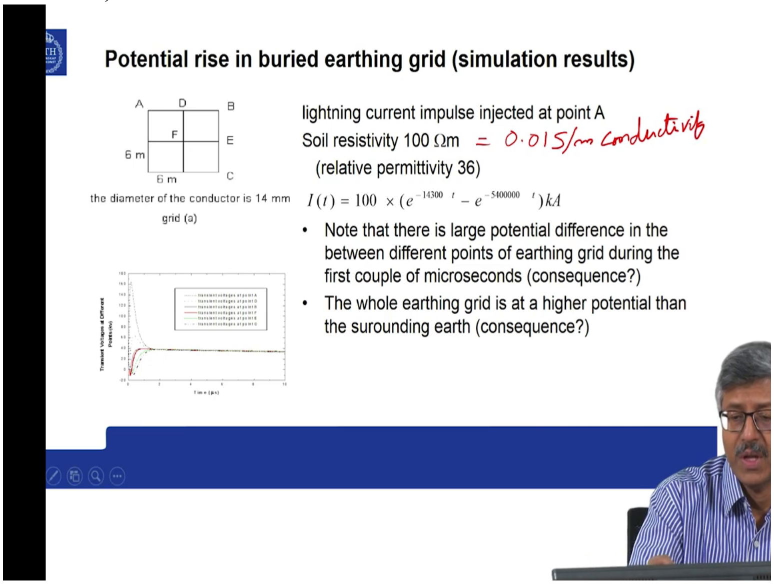

So this is 1 over resistivity 1 by R. let us say.

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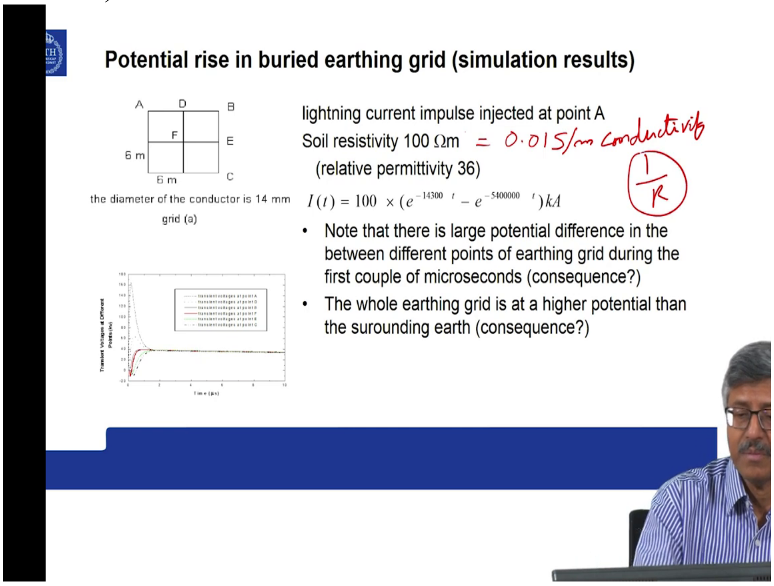

So the current is injected to one corner then you are measuring the voltages, transient voltages at various nodes. You can see that within the first two microseconds you do not have any equipotential grid here. There are huge potential difference at various points.

Only after that you reach a steady value and when you reach a steady value you can see that this around 40, 40 k V,

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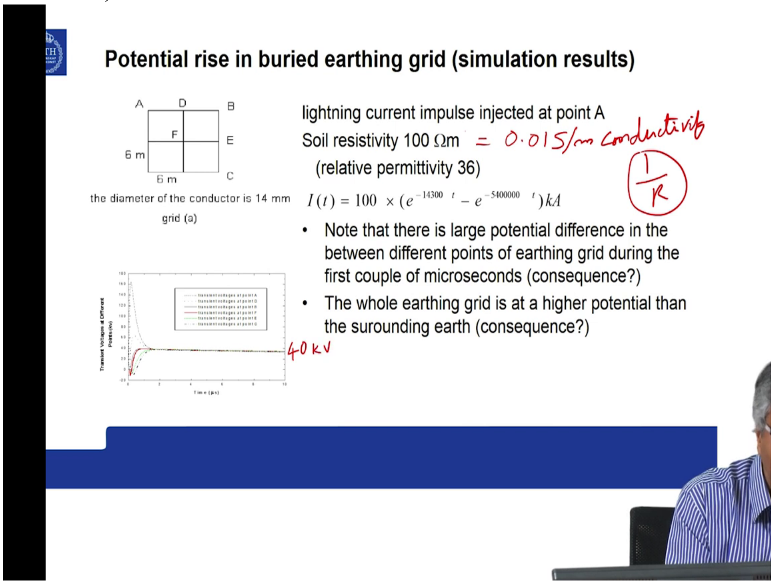

around 40 k V. The board grid goes up in potential to 40 k V and that may drive currents to adjacent systems.

So now here more or less equipotential but again it is at a higher potential level during lightning strike and during this time you do not have any equipotential during the first couple of microseconds.

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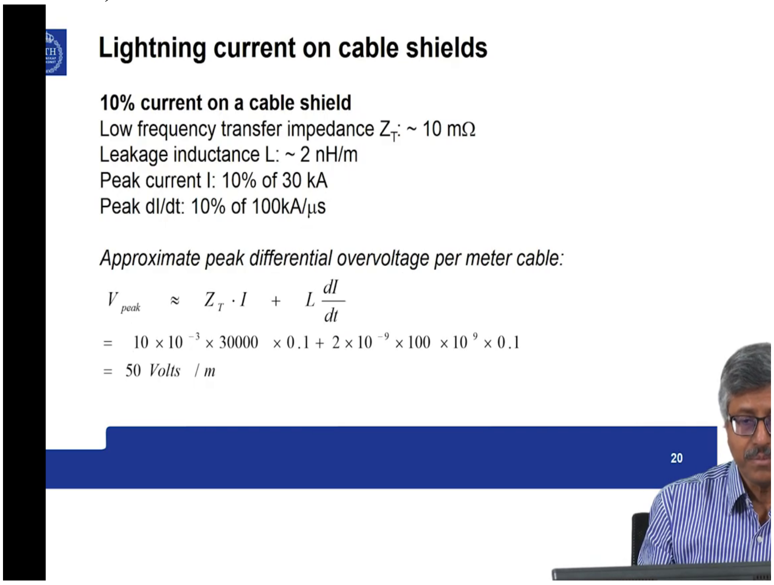

So this one has to be aware of.

So if you have one system connected here and another system connected here, then through the cable of the systems you can have very large currents following because of the potential difference between those two points during the first two microseconds.

Lightning current on cable shields, we have seen the transfer impedance of cable shield before. Suppose 10 percent of lightning current is in a cable shield. The low frequency transfer impedance is let us say, 10 milli ohms which is a D C resistance.

And the leakage inductance which indicates how much magnetic field will penetrate through the shield; let us say it is 2 nano Henry per meter.

Then peak, 10 percent of peak current and 10 percent of d I by d t so even though we cannot add this part which is more or less resistive and this is inductive part, let us say, approximately let us add that and see how much voltage we will get.

So this is altogether you get around let us say, of the order of 50 volts per meter. So as the current is traveling along the cable, even though it is 10 percent of lightning current, 50 volts open circuit voltage between the shield and the current

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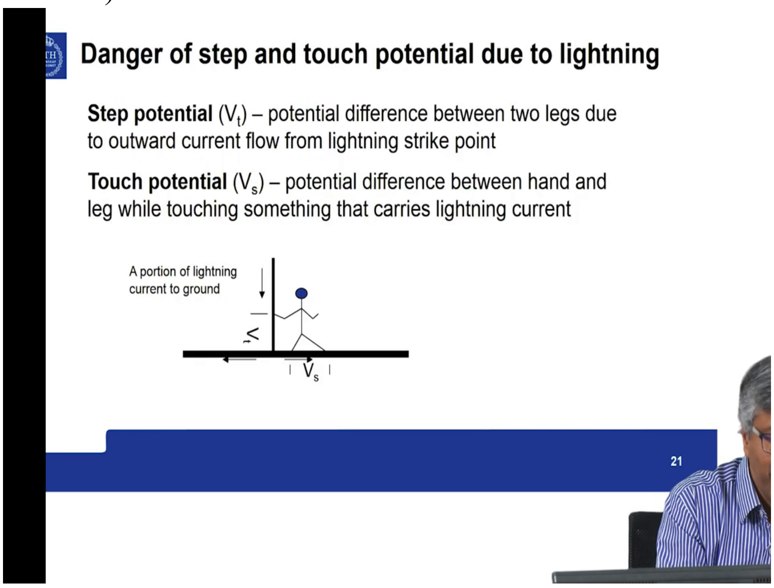

will be produced

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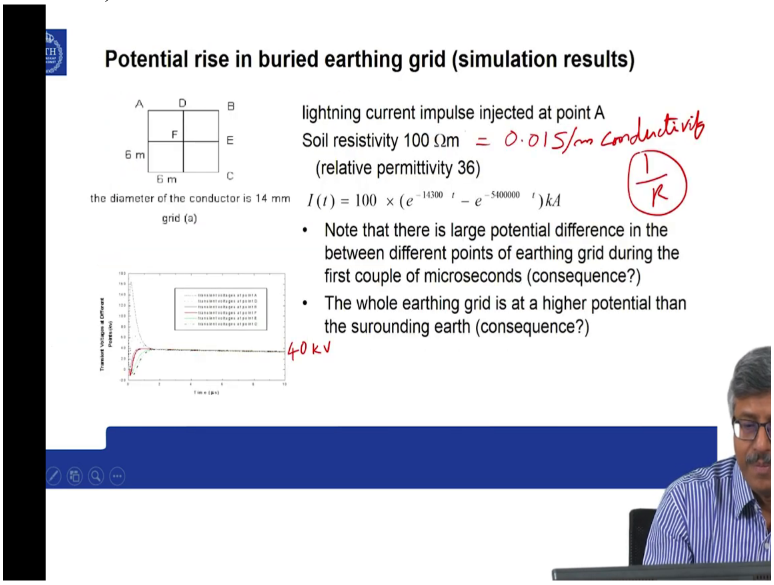

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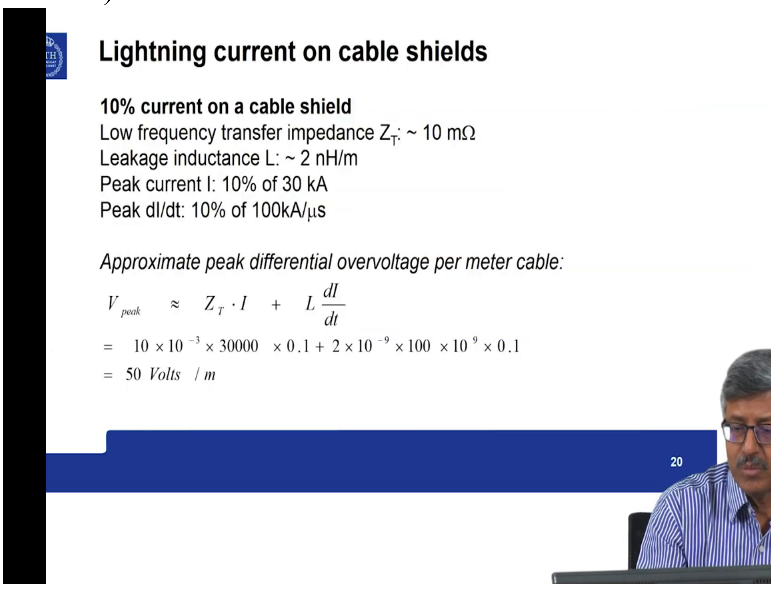

So this is the ind (()) (43:16), so here if you measure the voltage, so this voltage is almost equal to 50 volts per meter of this line.

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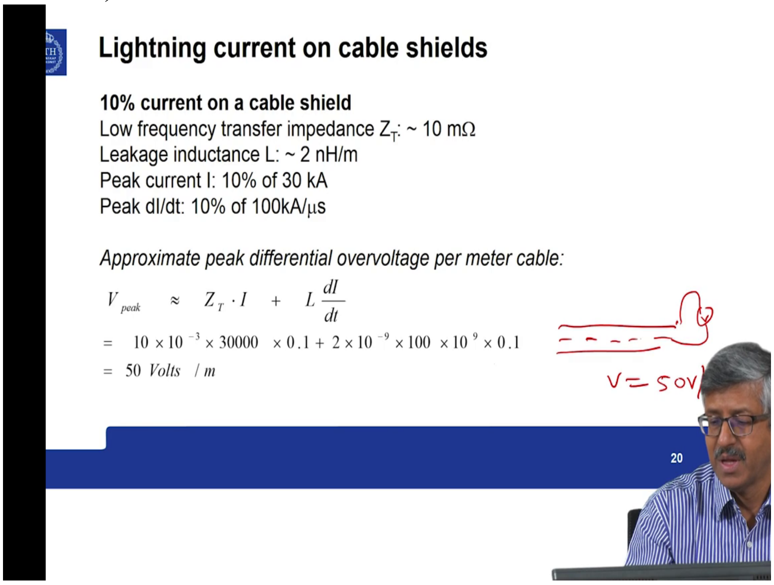

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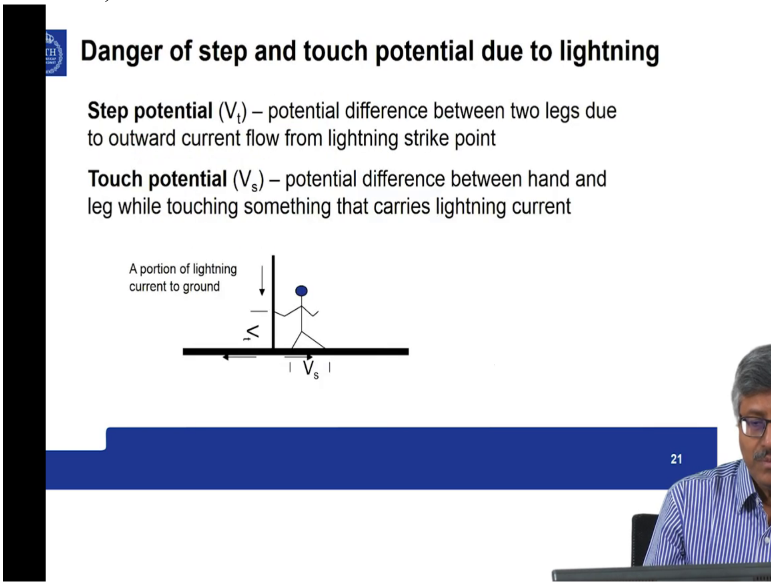

The step and touch potential due to lightning. One purpose of lightning protection is to reduce the step potential and the touch potential to those values that are not harmful for human beings. So step potential is defined like this.

So if you have some horizontal current flow or if you have an horizontal electric field it will drive some currents and between the legs of a person it can create certain potential difference. So the lightning protection system should be designed in such a way that this potential is not harmful for the person.

Similarly if the person is touching any part of the lightning conductor system there is the potential difference between the hand and the feet and this voltage called touch potential should not be above a value that is harmful to the person.

So this concludes regarding the properties and next we will go into more on actual protection principles from lightning.