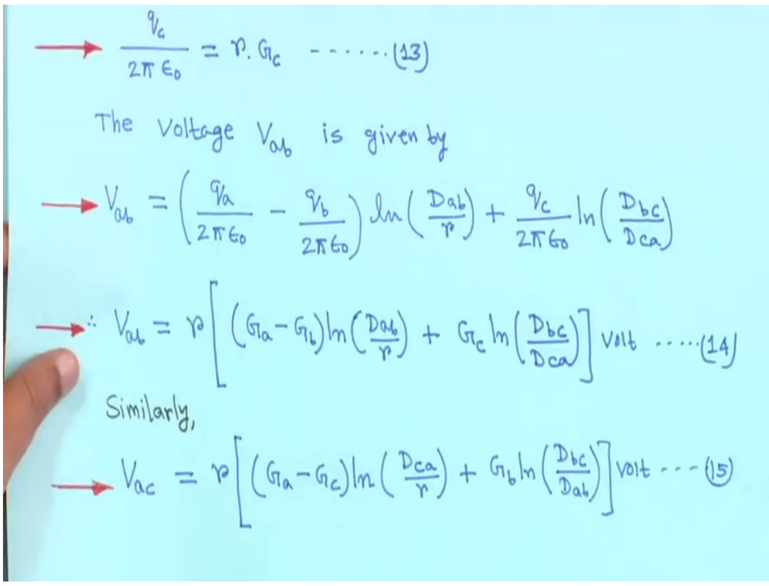
Power System Engineering
Prof. Debapriya Das
Department of Electrical Engineering
Indian Institute of Technology, Kharagpur

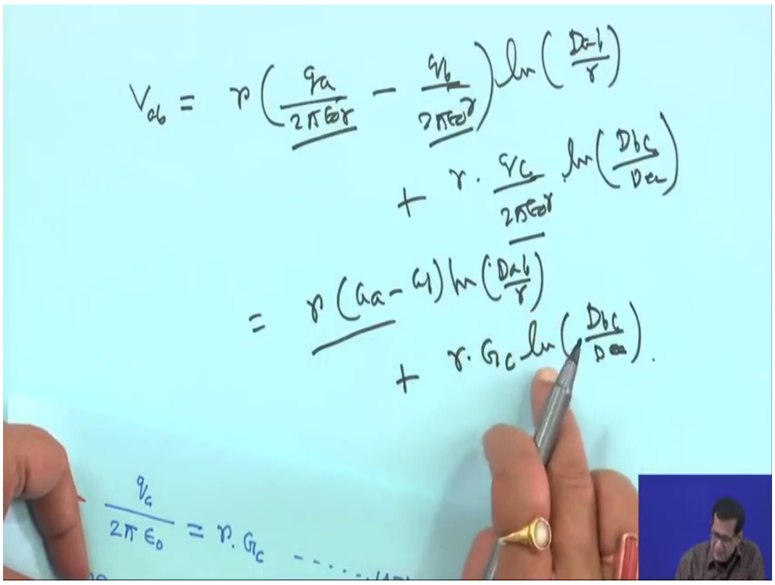
Lecture - 21
Corona (Contd.)

(Refer Slide Time: 00:17)



Welcome back, now question is how these things are coming r into this thing. So, first equation is this, Vab is equal to what you do here numerator and denominator, here you multiply by r right? Then your Vab is equal to, if you multiply by r it will be qa upon 2 pi epsilon 0 r, minus your qb divided by 2 pi epsilon 0 r, then ln Dab upon r plus, this term numerator and denominator you multiply by r, it will be r into qc upon 2 pi epsilon 0 then r, right? Ln your Dbc divided by Dca right?

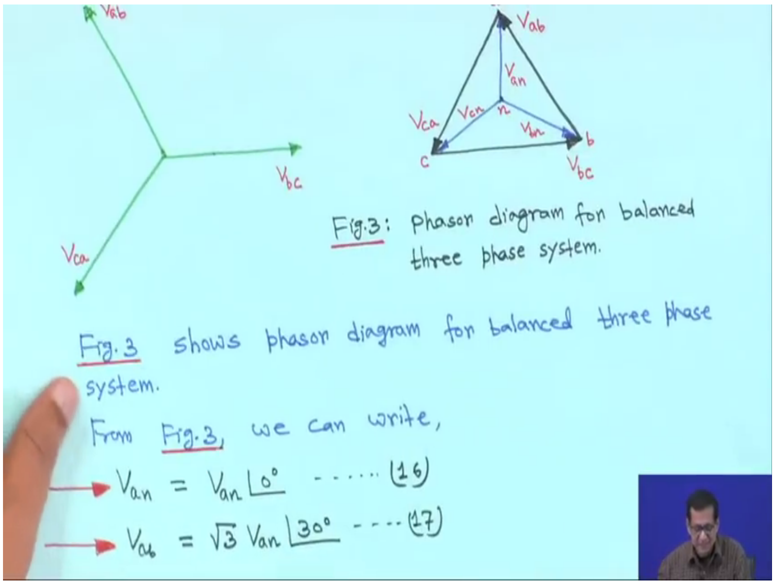
(Refer Slide Time: 00:29)



So, this is actually Ga, this just now we have given this is Gb and this is Gc. So, it will be actually r into Ga minus Gb ln, Dab upon r plus, r into Gc ln Dbc upon Dca right; that means, you take r common. So, it will be Ga minus Gb into ln Dab upon r plus, Gc ln Dbc upon Dca. So, that what we are writing here, that Vab is equal to r into Ga minus Gb ln Dab upon r plus this term.

Similarly, Vac also same way, you can you will get the same thing easy to remember. Look Vabd is there r is there Vab. So, Ga minus Gb ln Dab upon r and, other thing is that phase c. So, that is this Vab actually. So, phase for phase Gcln Dbc upon Dca right? So, and similarly for Vac you can write r into Ga minus Gc ln Dca upon r plus Gb ln Dbc upon Dab this is volt, right?

(Refer Slide Time: 02:25)

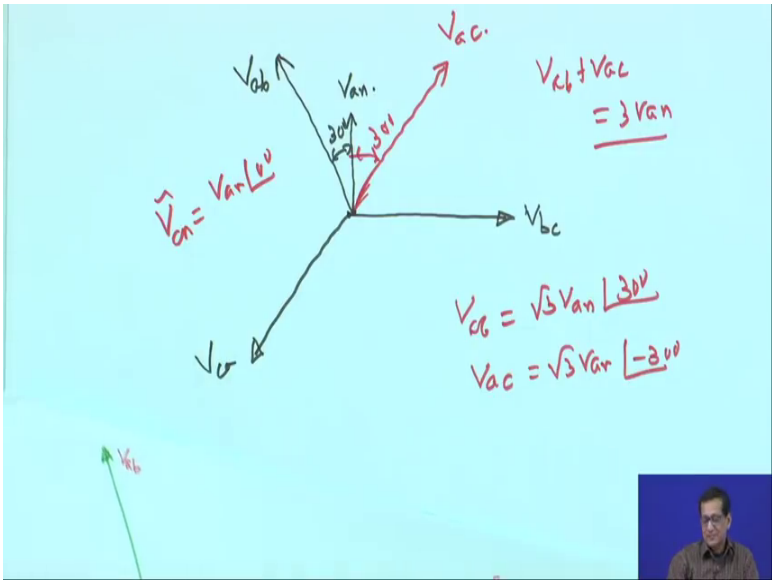


Now, this next we will come to the phasor diagram, that we have to establish some condition this actually, we have seen in the capacitance chapter and all things are, I mean detailed in given everything is given there, right? If you those who have taken that course they know it, those who have not taken this course, I request them please go through that capacitance chapter everything is given right?

So, before proceeding further, look at this phasor suppose this is your Vbc this is Vab and this is Vca. So, using this make a triangle, here right? So, this is Vbc, my Vbc and this is Vab, it is moving like this. So, Vab so, parallel I mean this is Vab. So, make Vab. So, Vbc b is the when you make ab bc ca? And arrow tip right? So, it is Vbc. So, this you occur b for your understanding and it is arrow tip Vab is first coming b, wherever first your what you call that, phase is coming bc to bc means b phase, c phase b is coming it will be ab. So, it is a ca arrow tips is here it will be c right. So, question is that, and your this is your Vbc, this is your Vab and this one Vca going down. So, Vca so, this way first to complete the triangle, right? Understandable nothing is new, I am doing it is simple this is Vbc, this is Vab make Vab and Vca. So, make Vca right?

Then you assume the neutral point is there n. So, this is because of Vbc arrow tip is here. So, it is b this Vab arrow tip is here for Vab. So, a and Vca this is c. So, it is a, it is b, it is c, next is this term neutral you make it, then this voltage will be Van, this voltage will be Vbn and this voltage will be Vcn, arrow tip is here for an bn and cn here right?

(Refer Slide Time: 04:30)



Now, next mention that then if, you then further I have not done, I will make it here for you now, suppose if you have you have this is Vbc, this is your Vca, drawing may not be symmetrical, but understandable, but this is your Vab right? Now this is Van, right? So, if you if you look into that, Vab Vca if you look into that and, if you that mean this is your Van. So, that is your Van this angle is 30 degree, right? This you know right this angle is 30 degree.

Now, it is Vca; that means, your Vab actually leading Van 30 degree or Van is your what you call lagging for Vab by 30 degree and, this is Vca if you change this one just opposite it is Vca, then it will be your Vac right? Then this angle also 30 degree right; that means, if you take your Van as a reference for example, an angle between Van and Vbc is 90 degree right? Angle between Van and the way phasor is drawn, angle between Van and Vbc it is 90 degree, right?

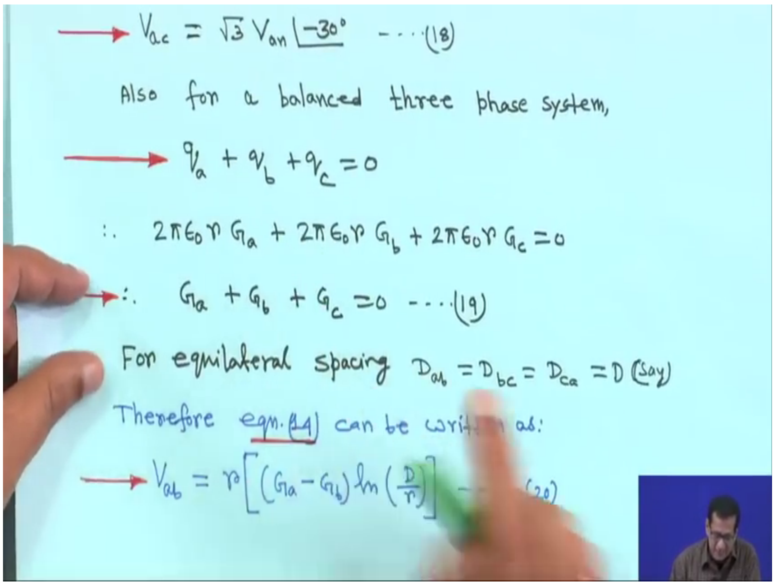
So, if you call; that means, we have seen earlier that Vab and Vbc is equal to 3 Van, this is we have seen our capacitor chapter. So, question is that, here also same thing that, if you take Van as the reference then suppose Van is equal to Van angle 0, right? Then Vab will be root 3, because it is a phase voltage it is a line, it is a phase voltage that is phase to neutral and it is line to line voltage.

So, Vab will be root 3 Van suppose if you take for example, if you take say Van is equal to Van angle 0 degree, right? If you take suppose this is phasor quantity. So, Van angle 0.

So, Vab will be root 3 Van, but angle will be plus 30 degree, because it is leading suppose if my Van is the reference, right? Then then Vab will be root 3 Van this one similarly, Vac it was Vca because we have taken one 80 degree opposite that is why, Vac right? Vac will be also root 3 Van, but angle will be minus 30 degree, because if this is reference it is lagging. So, it is minus 30 degree, right? Suppose it is understandable to you.

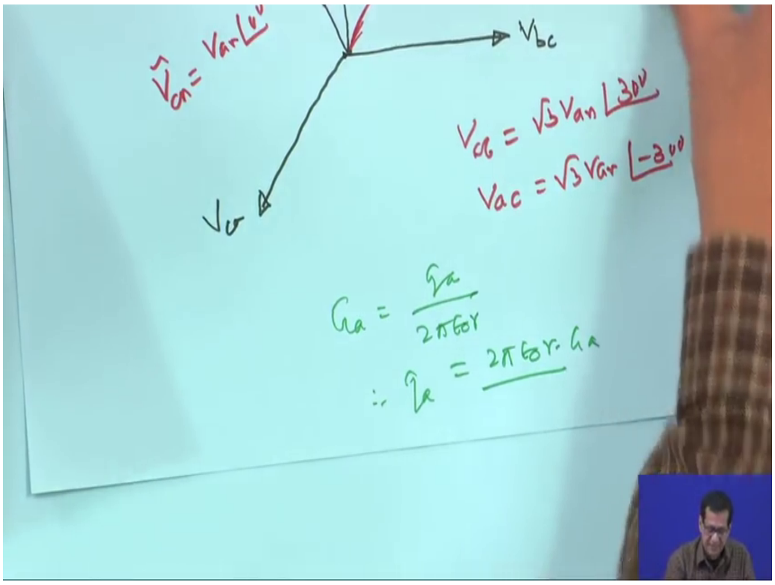
So, similarly; that means, what we are doing actually Van, we have you are taking as reference say, Van angle 0 degree therefore, Vab actually root 3 Van angle 30 degree, this 16 this 17-equation number, that is why your I have written that, is why Vab root 3 where this is, you take as a, then only then things analysis will easier right? And it Vca. So, just 180-degree opposite, we have might change this polarity it is Vac.

(Refer Slide Time: 07:57)



So, similarly then Vab is equal to root 3 Van 30 degree now similarly your Vac is equal to, I just showed you root 3 Van angle minus 30 degree this requires an 80, also for a balanced 3 phase system, if it is balanced qa plus qb plus qc is equal to 0, this is known to you right? And hence we are writing actually, this one were what we call, just hold on, here I am writing right? We know Ga is equal to qa upon 2 pi epsilon 0 r, that means qa is equal to 2 pi epsilon 0 r into Ga similarly, for qb 2 pi epsilon 0 r into Gb and qc will be 2 pi epsilon 0 r into Gc right?

(Refer Slide Time: 08:21)

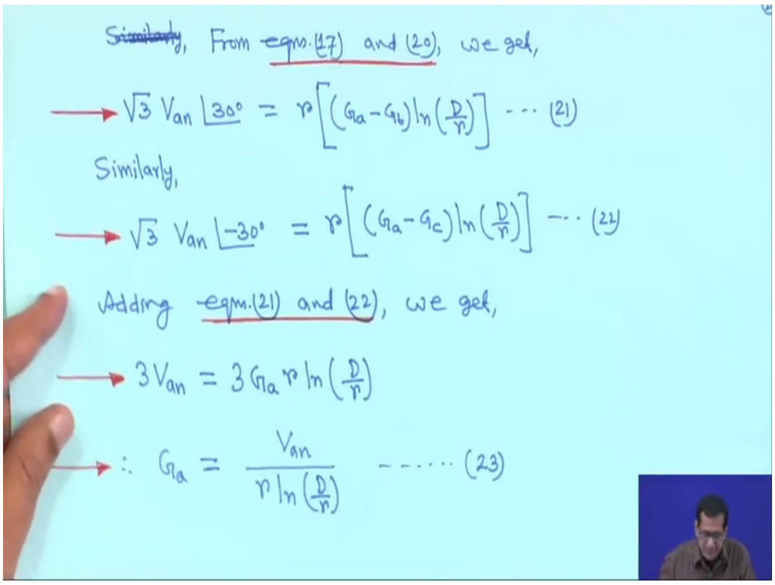


That means instead of q, you can write 2 pi epsilon 0 r Ga, plus 2 pi epsilon 0 r Gb plus 2 pi epsilon 0 r Gc therefore, this 2-pi epsilon r is common. So, it will be not it will not be there. So, Ga plus Gb plus Gc is equal to 0 using 19; that means, for balance system, if qa plus qb plus qc is 0 then, potential gradient also Ga plus Gb plus Gc is equal to 0 this is equation 19, right?

Now, if you assume equilateral spacing, for a special case say Dab is equal to Dbc is equal to Dca, is equal to D say therefore, equation 14 can be written as, right? I mean this equation because all are same. So, I mean Dab Dbc Dc all are same. So, it will become D upon D this term vanish, it will become 0, this term will vanish, similarly here also this term Vanish. So, Vab Vac this term will vanish right?

So; that means, in equation 14 it can be written as your Vab is equal to r, into Ga minus Gb ln D upon r this is equation 20, right? And we have seen that Vab is equal to root 3 Van your angle 30 degree that, you have seen. So, this Vab you can write that from equation 17 we have seen, it is Vab is equal to root 3 Van angle 30 degree that is why writing from equation 17 and 20 is equal to r, into Ga minus Gb ln D upon r this is equation 21.

(Refer Slide Time: 10:06)

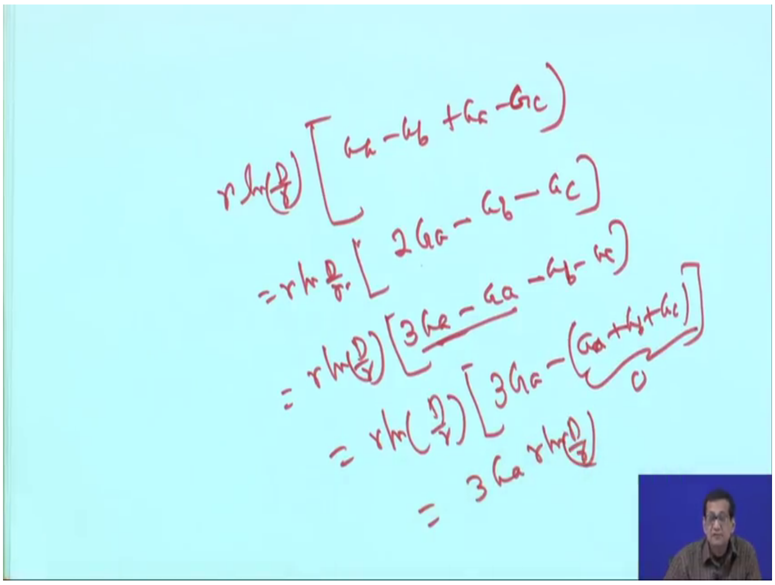


Similarly, we can write Vac also ab Vcca. So, Vac you have made it, Vac is equal to root 3 Van angle minus 30 is equal to r, Ga minus Gc ln D r, right? This right-hand term, this is coming from equation 15, in that case the third term will be here, what you call will be vanished right?

Now, if you add these 2 this root 3 Van angle 30 and root 3 Van angle minus 30, if you add these 2 then, you will get 3 I told you that Vab plus Vac is equal to 3 Van, we have seen in the capacitance chapter, right? So, this if you add these 2, it will become 3 Van left hand side, right hand side will become 3 Ga r ln D upon r or Ga is equal to Van r ln D upon r.

Now, if you add these 2 how I will show only the right-hand side, that how things are coming right? If you add these 2 equation 20 and 21, 21 and 22, if you add then it is coming actually.

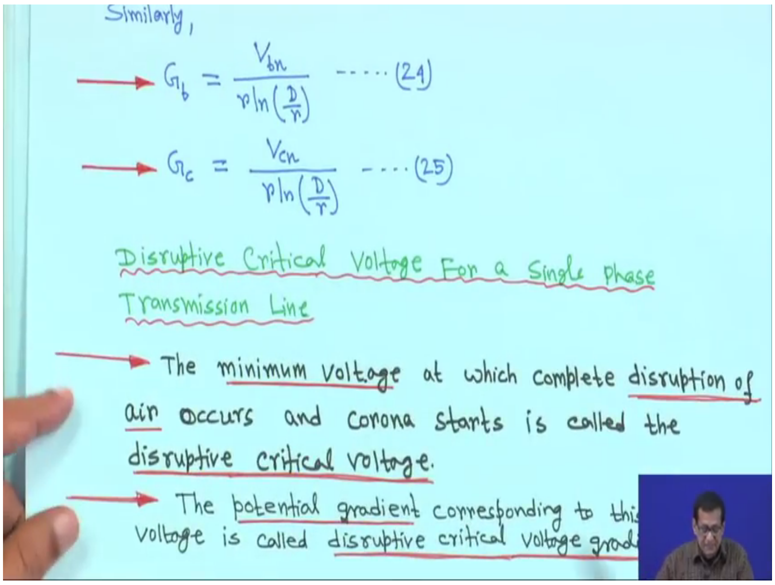
(Refer Slide Time: 11:26)



If you take r common right? Then and ln D r, D upon r D, r upon r both are common. So, r l n D upon r this is also common. So, in bracket it will be Ga minus Gb, plus the Ga minus your Gc it will be like this right?

So, in that case if you see that, this is your r ln D upon r, right? And this will be 2 Ga minus Gb minus Gc this one actually r ln D upon r then you add one Ga, it will be 3 Ga then minus Ga minus Gb minus Gc. So, this 2 Ga we are writing, 3 Ga minus Ga this thing, right? And which is minus Gb is there minus Gc is there. So, is equal to r ln D upon r. So, it is actually you can write, 3 Ga minus, Ga plus, Gb plus Gc right, but we have seen Ga plus, Gb plus, Gc is equal to 0. So, this term is 0, that is why it is 3 Ga r ln D upon r that is, why we are writing this one that your 3 Ga, 3 Van is equal to 3 Ga r ln D upon r. So, 3 3 will be cancelled and therefore, Ga is equal to Van upon r ln D by r this is question 23 this is for phasor conductor, right? Ga potential gradient.

(Refer Slide Time: 12:54)

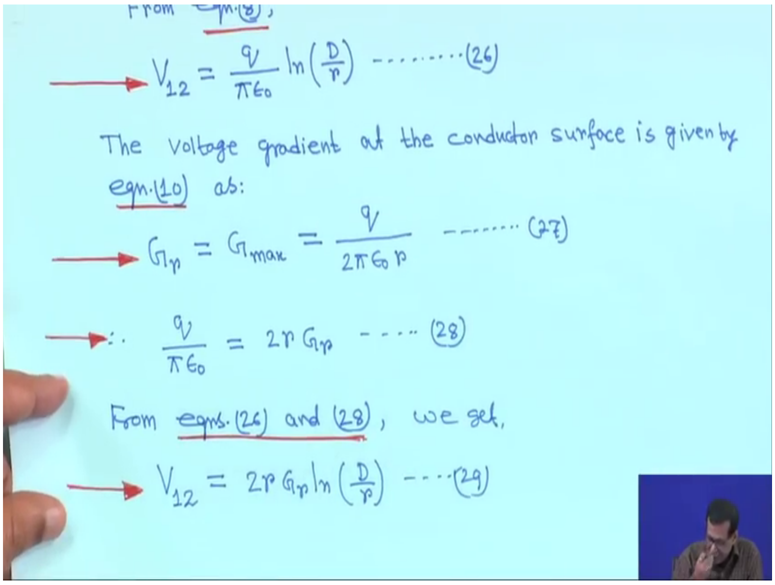


Similarly, Gb also similarly it will be like this, Vbn upon r l n D upon r and Gc will be Vcn upon r ln D by r this 24, very easy to remember right now next is. So, this is I hope this is understandable to all of you right?

Next is disruptive critical voltage for a single-phase transmission line, first we will consider single phase then, we will move over to 3 phase. So, the minimum voltage at which complete disruption of air occurs, and corona start is called the disruptive critical voltage right? This is the minimum voltage require that, it will be here that there will be complete disruption of air, surround a conductor right it occurs and corona start is called the disruptive critical voltage.

Now, the potential gradient corresponding to this value of the voltage is called disruptive critical voltage gradient, I mean for this whatever potential gradient, you will get for this condition is called the disruptive critical voltage gradient, right? Now from equation 8, just hold on from equation 8, we have seen that for single phase line that V12 is equal to q upon pi epsilon 0 ln D upon r this is equation 26.

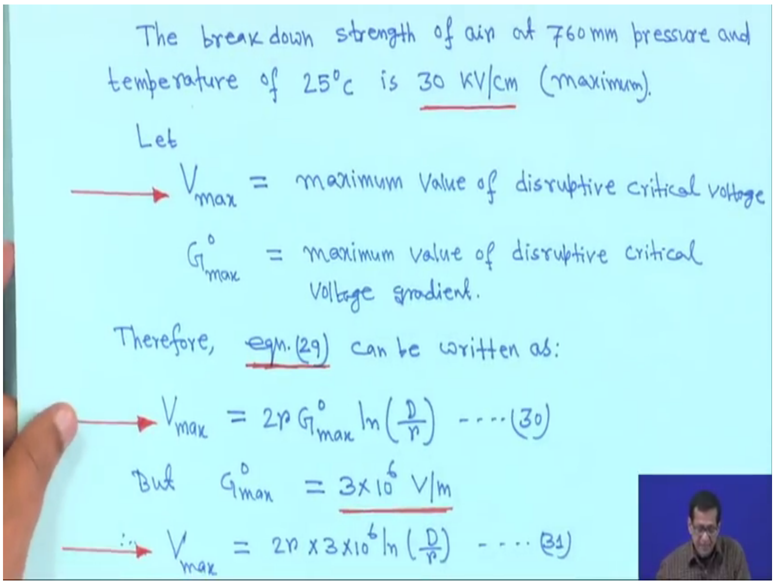
(Refer Slide Time: 14:04)



The voltage gradient at the conductor surface is given, by from equation 10 only we have seen that is that maximum Gr is equal to Gmax that is at the surface of the conductor, that is q upon 2 pi epsilon 0 r. This is equation 27 or you can write q upon epsilon your pi epsilon 0, you can write just cross multiply by 2 r. So, q upon pi epsilon 0 is equal to 2 r, Gr this is equation 28, right?

And this q upon pi epsilon will 2 r Gr you substitute in equation 26, here substitute if you substitute that, is why I am writing from equation 26 and 28, we get V12 is equal to 2 r into Gr l n d upon r this is equation 29 right?

(Refer Slide Time: 15:07)



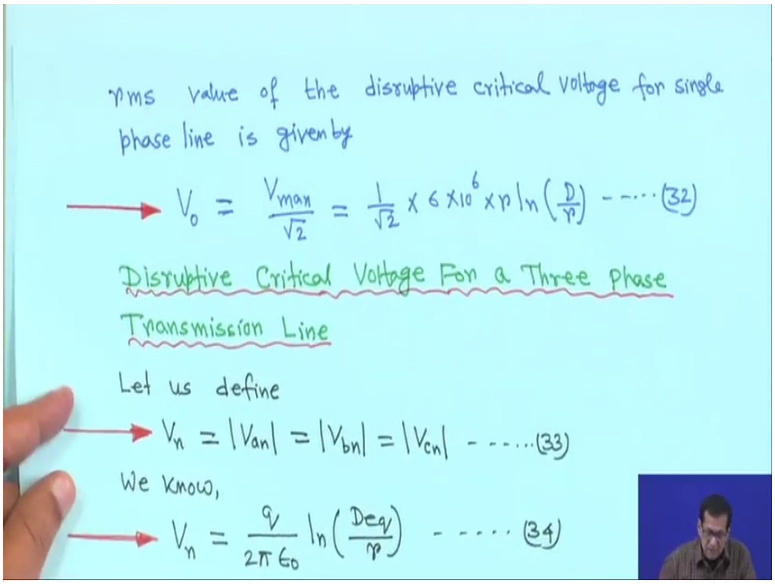
So, the breakdown actually strength, of air at the atmospheric pressure that, is 760 mm pressure and temperature of 25 degree Celsius, is 30 kilovolt per centimetre, this is the maximum, this is the breakdown strength of the air, now you assume Vmax is equal to maximum value of disruptive critical voltage.

Let us you define, the Vmax is the maximum value of the disruptive critical voltage, and Gmax superscript 0 Gmax 0 is equal to maximum value of disruptive critical voltage gradient. Therefore, equation 29 can be written as Vmax is equal to 2 r Gmax 0 right ln D upon r. So, this equation this equation, instead of V12 we will make this is Vmax, right?

So, Vmax is equal to 2 a Gmax 0 ln D upon r, but Gmax 0 is your 30 kilovolt per say send your centimetre, which is equal to actually 3 into 10 to the power 6 volt per meter. So; that means, V max is equal to 2 r into 3 into 10 to the power 6 ln D upon r. So, this is the maximum voltage right. So, these are your of course, r in r will be in meter, because we are writing it is volt per meter. So, r will be in meter. So, this is volt, right?

So, this r m s value will be, of this voltage, right? Maximum disruptive critical voltage it will be divided by root 2. So, the rms value of the disruptive critical voltage for single phase line V0 will be Vmax upon root 2.

(Refer Slide Time: 16:39)

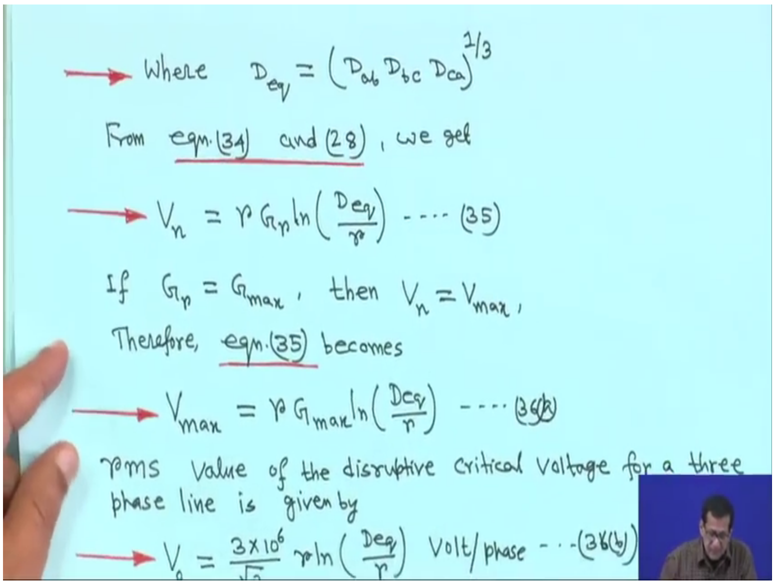


So, it will be 1 upon root 2 is equal to 6 into 10 to the power 6 r ln D r, because this is 2 r into 3 into 10 to the power 6. So, 2 into 3, 6 that is why we are writing as 6 into 10 to the power 6 into r and divided by root 2 ln D upon r. So, this is equation 32. So, this is your what you call V0, that is that rms value of the disruptive critical voltage, right?

Next is disruptive critical voltage for a 3-phase transmission line, now let us define say magnitude Vn is equal to Van, is equal to Vbn is equal to which there magnitudes are same this is equation 33, now we know this thing, the Vn is equal to q upon 2 pi epsilon 0 ln D e q by r, this we have seen right? This we have seen.

Now, where D e q is equal to your, what you call that Dab Dbc Dca to the power 1 by third, this is your this we have seen in capacitance chapter, right? Therefore, we know this that q upon 2 pi epsilon 0 ln D eq upon r, right?

(Refer Slide Time: 17:57)

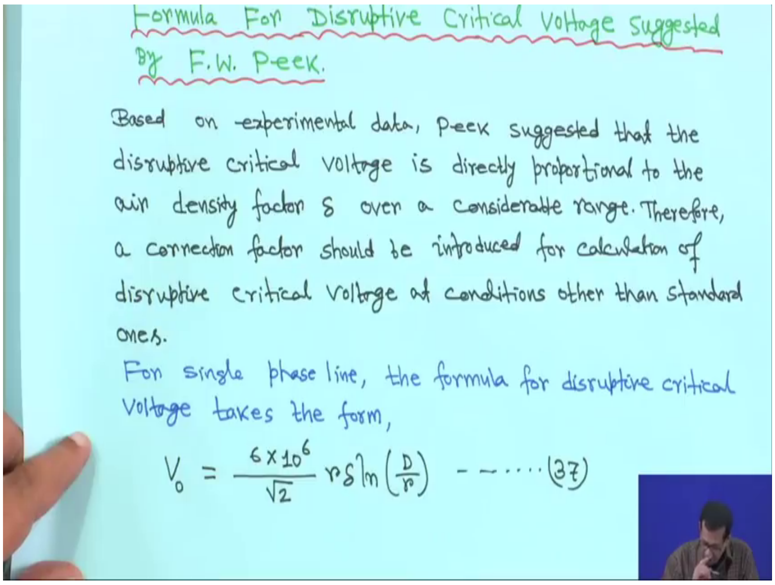


That means in equation from equation 34 and 28, you will get. So, in equation 30 if you go back to equation 34 and you this and 28, this is your equation 34 this 28, is q upon pi epsilon 0 2 r Gr, right?

So, from this equation, we get that Vn is equal to rGr ln Deq upon r this is equation 35 therefore, that from equation 35 actually, become this equation Vmax is equal to rGmax ln Deq upon r, because V n is equal to Vmax and if you put, Gr is equal to Gmax because, at the surface of the your this thing of the surface of the conductor potential gradient is maximum, that is at x is equal to r right therefore, at the time in that case Gr will be Gmax and then, Vn will be Vmax therefore, this equation we can write instead of Vn we can write V maxr and Gr should be replaced by Gmax, ln deq Deq upon r this is equation 36 a I have marked it as a 36 a actually.

Now, rms value of the disruptive critical voltage for a 3-phase line, it is just divide by root 2. So, it is 3 into 10 to the power 6, because Gmax is 3 into 10 to the power 6 divided by root 2, then r this 3 into 10 to the power 6, your volt per meter and r has to be taken in meter, when you solve the numerical or. So, 3 into 10 to the power 6 upon root 2 r ln Deq upon r, this is volt per phase this is 36 b, right?

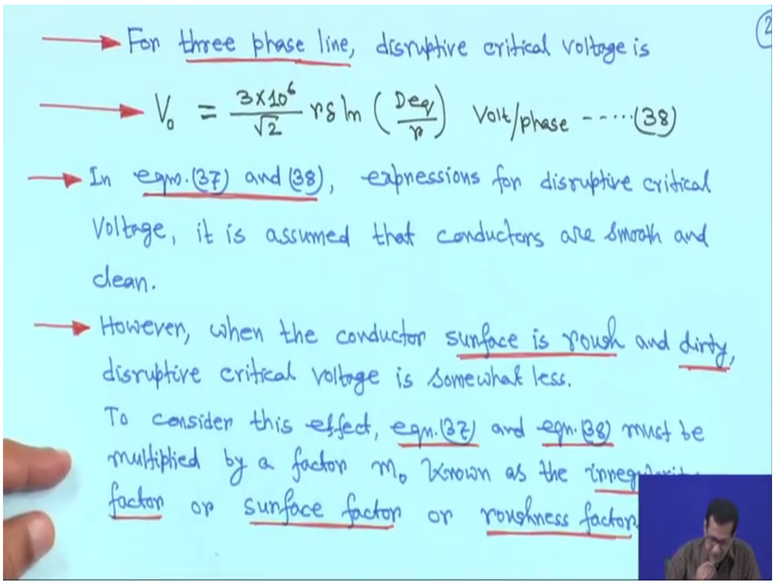
(Refer Slide Time: 19:40)



Now, next is the formula for disruptive critical voltage, suggested by FW peek, that is see here suggested something. So, based on experimental data peek suggested that, the disruptive critical voltage is directly proportional to the air density factor delta, over a considerable range therefore, a correction factor should be introduced, for a calculation of disruptive critical voltage, at conditions other than standard ones, right?

Therefore, for a single-phase line, the formula for disruptive critical voltage takes the form, everything is same only delta 3 is multiplied right? So, the formula for this take the form V0 is equal to 6 into that, is air density factor delta, right? 6 into 10 to the power 6 upon root 2, this is your rms value right r delta ln D upon r. So, this air density factor delta has to be multiplied right?

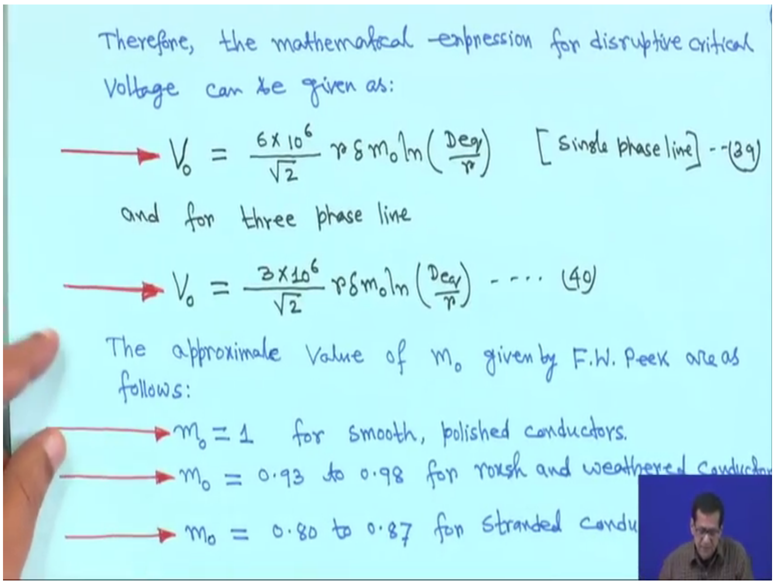
(Refer Slide Time: 20:41)



For 3 phase disruptive critical voltage same thing that, this thing that rms 1, that is your V0 is equal to 3 into 10 to the power 6, by root 2 r delta ln Deq upon r volt per phase, equation 38, now in equation 37 and 38, expression for disruptive critical voltage, it is assumed that the conductors are smooth and clean. That is surface is smooth and clean no dot nothing is there, based on that this is for 3 phase and equation 37 same thing that is for single phase line.

But conductor surface is rough and dirty, the disruptive critical voltage is somewhat less, see in that case to consider the effect in equation 37 and 38 must be multiplied by factor call m0, known as sometimes we call irregularity factor or surface factor or roughness factor, this value will be less than 1, right?

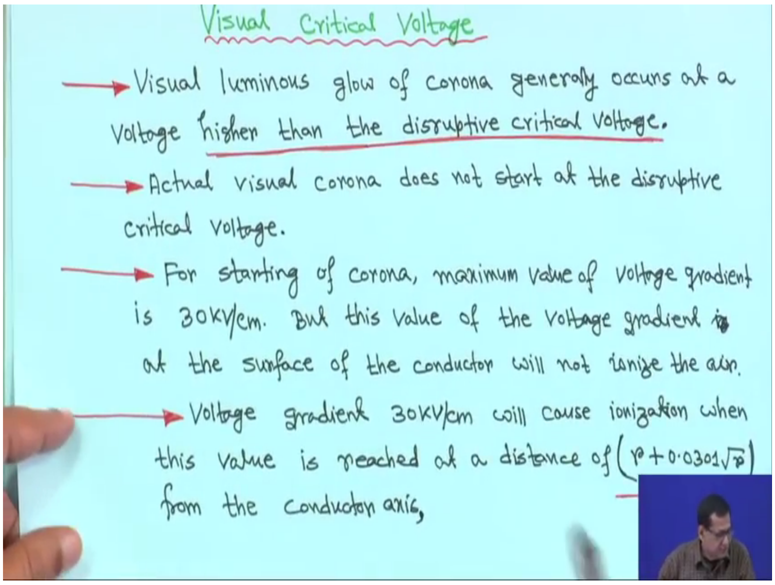
(Refer Slide Time: 21:40)



So, 3 terms are there irregularity factor, is conductor is not smooth right or surface factor or roughness factor, right? So, therefore, the mathematical expression for disruptive critical voltage can be given as, V0 is equal to same thing 6 into 10 to the power 6 upon root 2 r delta, was there the they multiplied by m 0 ln Deq upon r this is for single phase line, I have written here this equation 39.

And for the 3-phase line that, V0 will be 3 into 10 to the 6 upon root 2 r delta m 0 ln Deq upon r, this is equation 40. The approximate value of m0 given by FW peek are as follows m0 is equal to 1, for smooth polished conductors, m0 actually you can take in between 0.93 to 0.98 for rough and weathered conductors, right? And for m0 is equal to 0.8 to 0.87 for stranded conductors, right? So, these are the some after you know. So, after several testing other thing, he has made this kind of some range of this m0 value, but in reality m0 is equal to 1 may not be there, either this one or this one, right?

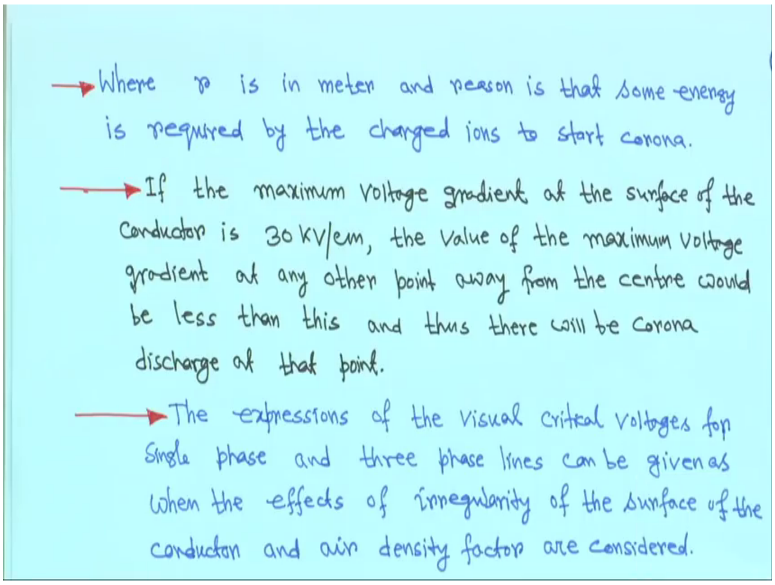
(Refer Slide Time: 22:49)



Next one is visual critical voltage, this is actually this is that visual luminous glow of corona, generally occurs at a voltage higher than the disruptive critical voltage, right? So, you have to find that voltage. So, we have to see that actual visual corona, does not start at the disruptive critical voltage. So, the corona which will be visible that voltage is greater than, the your disruptive critical voltage, for starting of corona maximum value of voltage gradient is 30 kilovolt per centimetre, but this value of the voltage gradient at the surface of the conductor, will not ionize the air right?

Therefore, the voltage gradient the 30 kilovolt per centimetre, will cause ionisation when this value is reached at a distance of some empirical formula r plus 0.0301 root, over r from the conductor axis right. So, this is actually something is suggested right?

(Refer Slide Time: 23:50)

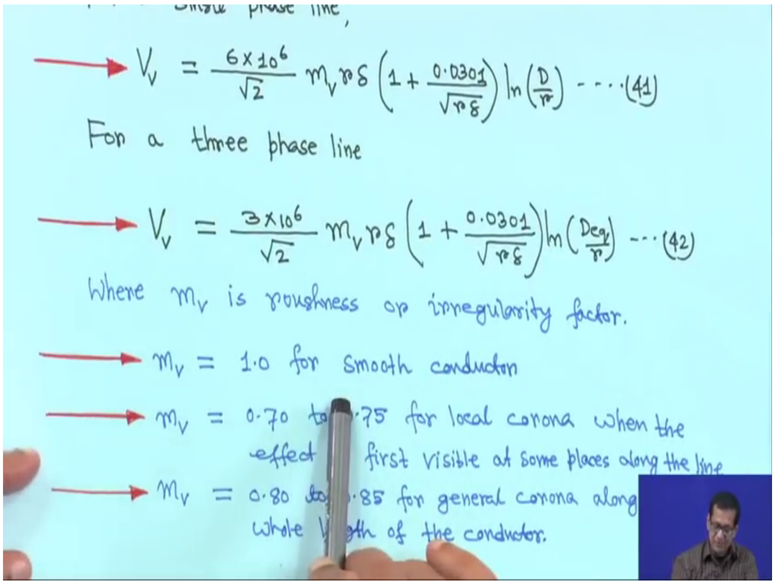


So; that means, r is that in meter and the reason is that some energy is required by the charged ions to start corona, right? Otherwise, that is why this r plus in approximately r plus that 0.0301 root r right?

So, that some energy is required actually, by the charged ions to start corona. So, if the max maximum voltage gradient of the surface of the conductor say, 30 kilovolt per centimetre. The value of the maximum voltage gradient, at any other point right away from the centre would be less than this, that is true right? If move away from the conductor, then naturally it will be less than that and thus there will be corona discharge at that point.

Therefore the expression of the visual critical voltage for the single phase and 3 phase line, can be given as when the effects of irregularity of the surface of the conductor and air density factor are considered, these are to some extent is empirical formula right; that means, this thing your what you call, for a single phase line that Vv, we are giving that visual critical voltage 6 into 10 to the power 6 upon root 2, then instead of you are making mv, this is another factor mv then r delta in bracket actually, what instead of r? What we are making it? R delta is there, but whatever making in bracket 1 plus point 0.0301 root over r delta ln D upon r, right? This is an empirical formula, actually right?

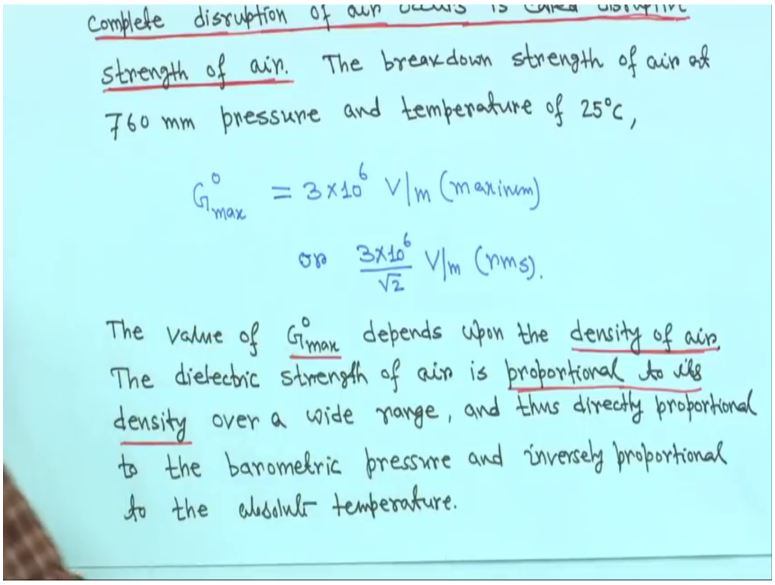
(Refer Slide Time: 24:55)



So, based on several field test, they have proposed. So, this is actually not coming from any derivation, at the these are we have seen, but these thing actually all through the field test, right? So, this way this formula can be written, for single phase line similarly for 3 phase line, what will happen that, it will 3 into 10 to the power 6 upon root 2 mv r delta is 1 plus 0, only this term is changing rest are same only instead of 6, here it is 3 rest are same right mv r delta 1 plus this is your 0.0301 divided by root over delta ln Deq upon r this is equation 42 right?

Where mv is the roughness or irregularity factor for this case, mv is equal to 1 for smooth conductor mv is equal to 0.7 to 0.75, for local corona when the effect is first visible at some places, along the line and mv is equal to 0.8 to 0.85, for general corona, along the whole length of the conductor right?

(Refer Slide Time: 26:44)

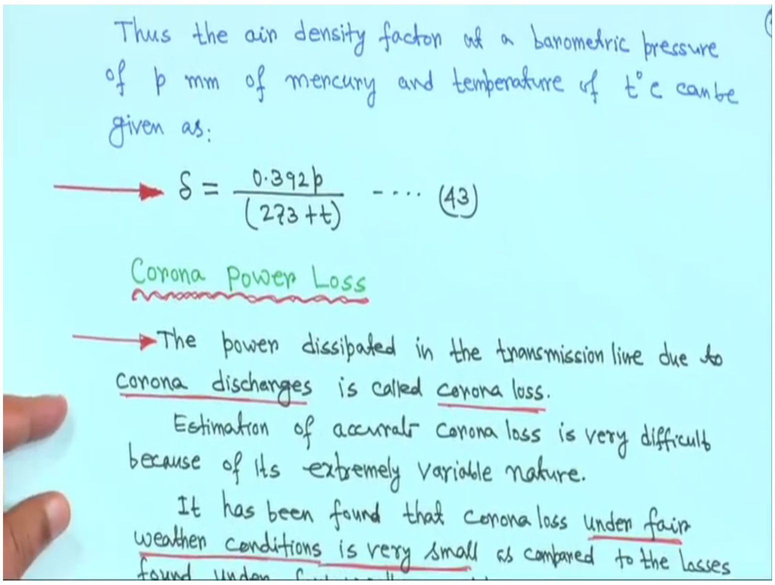


So, along the whole length of the conductor may be visible, but whatever little bit here and there I have seen, I have not seen this one, but localized I have seen it right? So, the value of the voltage gradient Gmax, at which complete disruption of air occurs is called a disruptive strength of air, right? That is the value of the voltage gradient Gmax at which complete disruption of air occurs, output that is called disruptive strength of air.

The breakdown strength of air, at atmospheric pressure, right? And temperature it is you know this thing, the breakdown strength of air, it is then is your 30 kv per centimetre, in general it is 3 into 10 to the power 6 volt per meter, this is the maximum or 3 into 10 to the power 6 upon root 2 volt per meter rms value.

So, value of Gmax 0 depends upon the density of the air, right this value depends on the dielectric strength of air, is proportional to it is density over a wide range, right? And thus, directly proportional to a your barometric pressure and inversely proportional to the absolute temperature. Based on that, air density factor, right? Some formula have been proposed I mean some your different field test or different testing and there is no proof, I cannot give you here, but some kind of empirical formula has been given.

(Refer Slide Time: 27:58)



Thus, that air density factor at a barometric pressure, of p millimetre of mercury and temperature say t degree celsius can be given as, delta is equal to 0.392 p divided by 273 plus t, this is equation 43 actually this Gmax 0, depend on the your density of air the dielectric strength of air is proportional to density, over a wide range, right; and thus, directly proportional to the barometric pressure and inversely proportional to the absolute temperature, right? That is why, this it is actually delta is proportional to p and delta is inversely proportional to 1 upon 273 plus t; that means, delta is equal to some constant k into p upon 273 plus t. So, that k constant actually is 0.392 right. So, delta approximately is equal to 0.392 p upon 273 plus t, this is equation 43.

Thank you very much, we will back again.