Power System Generation, Transmission and Distribution

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Lecture No. # 11

Capacitance of Transmission Lines

Good morning ladies and gentle man, last time we started with Transmission Line Parameters and we completed the inductance part of it. Today, we will be talking the second member of the family of the parameters of transmission line that is capacitance. Capacitance is equally important, if not more and it forms the shunt part of the line parameters, the only shunt parameters which is of importance, because the other one conductance is almost always neglected as already informed last time.

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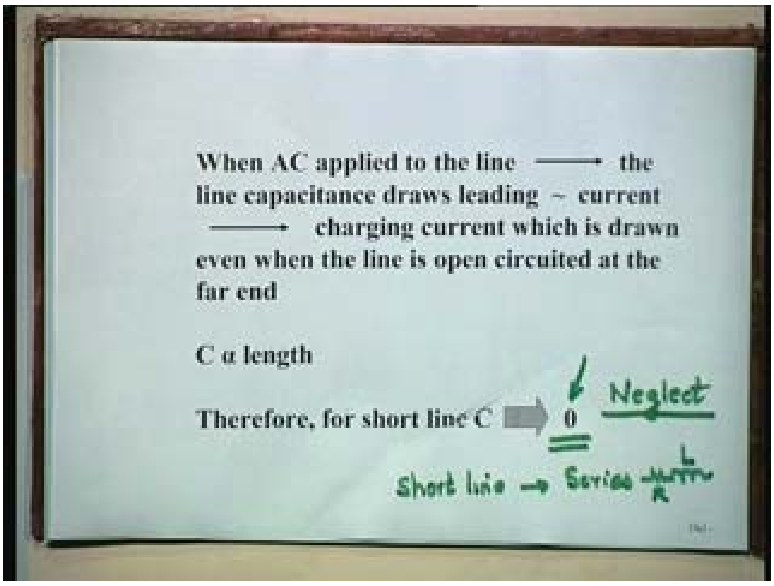

Whenever you pass an AC current to the line, the line capacitance draws leading current and charging current is drawn even when the line is open circuited at the far end; in fact because of this as you must have already learned in your under graduate, that is a effect called Ferranti effect and that is because of the capacitance. Now, capacitance is also proportional to the length line and that is why for short line, we almost always neglect it.

And as you know for short line, we employ just series model, that is r and inductance, no capacitance, it is zero and this is without loss of any accuracy, because it indeed is very small, there we will talking about magnetic field intensity. I am sure you must have learnt the concept of duality in circuit theory in third year or second year, what is dual? Resistance and conductance or inductance and capacitance or you are you know what you called Thevenin theorem and Norton's theorem these are all dual, concept of duality.

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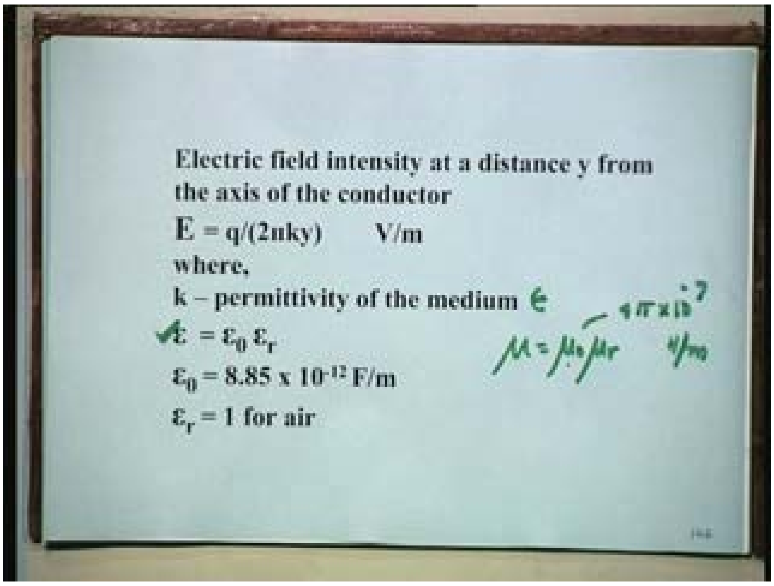

So, another concept of duality here is magnetic field intensity was there; here it is electric field intensity. So, electric field intensity at a distance y from the axis of the conductor is given by E is equal to q upon 2 pi k y, this k is permittivity of the medium; in certain books or certain authors call it epsilon, so I call it, again started calling it epsilon. Epsilon is equal to epsilon 0 into epsilon r like mu was equivalent to mu 0 and mu r, this was permittivity of the free space, this is of the medium, this is overall permittivity.

Similarly, the parallel analogous thing is permittivity epsilon 0 into epsilon r, this mu 0 was 4 pi into 10 is to power minus 7 henry per meter, so this is 8.85 into 10 is to power minus 12 farad per meter and epsilon r is of course 1 for air, like mu r was indeed 1 for air, this is a perfect duality or analogous properties shared by magnetic field and electric field.

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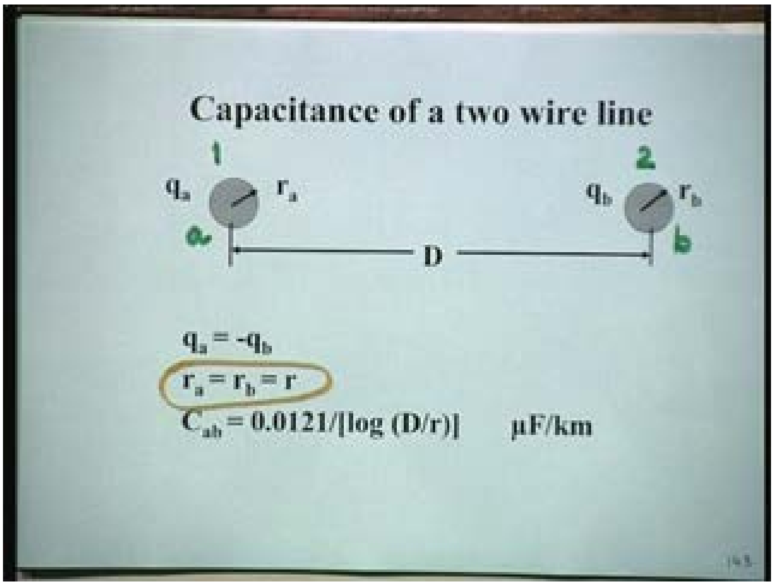

Now, as we have found out inductance of a two wire line, similarly we have to find out capacitance of a two wire line. So, as you can see in the figure, there are two conductors 1 and 2 or a and b whichever you want, they are shown of different sizes, but they can be of same size, in that case r a becomes r b is equal to r as you shown here. Their current was i a is equal to minus i a, here the charges are q a is equal to minus q b, D is the spacing between the two conductors, two wires; obviously, D is much larger than r, that goes without same. So, what is the capacitance between conductors a and b? 0.0121 upon log d by r, whenever I write log means to the base 10, whenever I write ln natural log means to the base e, one can be converted into another, that formula is known to you.

This is that was millihenry per kilometer, here the practical units are macrofarad per kilometer, you always talk of picos and nanos and micros and farads and of course electron is still smaller, but even in power lines it is microfarad per kilometer. This derivation you can see in the book if you want, but you must have already done it in your under graduate, I have no intension of repeating what you have already done.

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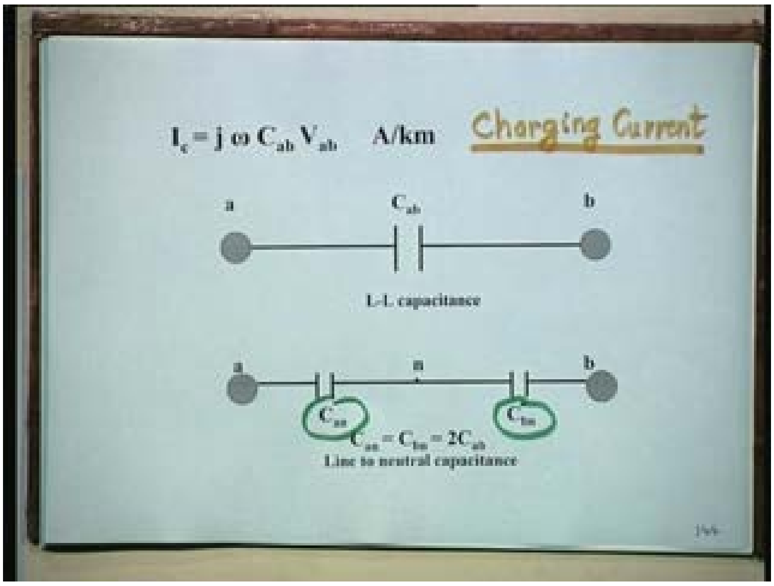

This is a very important parameter called charging current I c, obviously is equal to j omega c a b into v a b and it is again amperes per kilometer, omega as all of you know it is 2 pi f, f is frequency, which is normally 50 hertz or 60 hertz for any power lines. So, again I have redrawn the same figure of earlier pages a b, only difference is, here I am showing capacitance (()) of them, which is line to line capacitance C a b, the formula we have already computed 0.01 to 1 upon log of D by r. Would you notice that, r is no r dash here, this is nothing like internal flux, there it was so that is why 0.7788 times r is equal to r dash, but here there is nothing like r dash, it is r only and this is what the students normally go wrong, when they start using r dash also here, there is no r dash in capacitance.

I hope you will keep this in mind while solving problems, otherwise even your if whole problem is right and if you make r dash here; teacher is within his rights or her rights to give you zero, because they do not know any difference between capacitance and inductance, then do not say it is very minor point, it is a major point. Now, I can always replace C a b by two individual line to neutral capacitances, C a n and C b n. Obviously, C a n and C b n is equal to 2 C a b right, this is line to neutral capacitance, this n is a neutral point.

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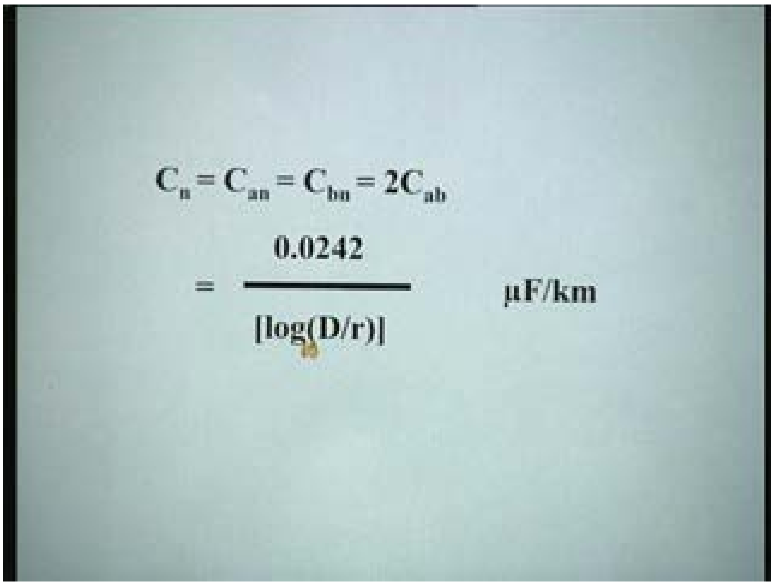

Suppose it is same, C a n and C b n which will be then, why have two a n and b n have C n capacitance will neutral, when both are same, then rise the question of a and b, so C n and that is equal to twice C a b and naturally that is same formula just multiplied by 2. So, you will get 0.0242 upon log of D by r, this log means 10 and as I am repeatedly saying, so that while you can computing do not making mistake and the units continuity to be same macrofarad per kilometer; if somebody wants you to find out in farads per kilometer, I am sure all of you are intelligent enough to multiply by 10 is to minus 6.

Remember one golden rule, if the units are large, then the number expressing them will be smaller; if you unit is smaller, than the number expressing them will be large; 100 paisa is equal to 1 rupee, rupee is a large unit, so only 1, paisa is a small unit, so 100. Many times you get confusion, whether you have to multiply by 100 or divide by 100, spatially when they are similar in a kilometer to miles, many people get confused should I multiply by 1.6 or should I divided by 1.6, there you should know at least this much mile is a bigger unit than kilometer, if you do not know that, then god only help you, then toss a coin.

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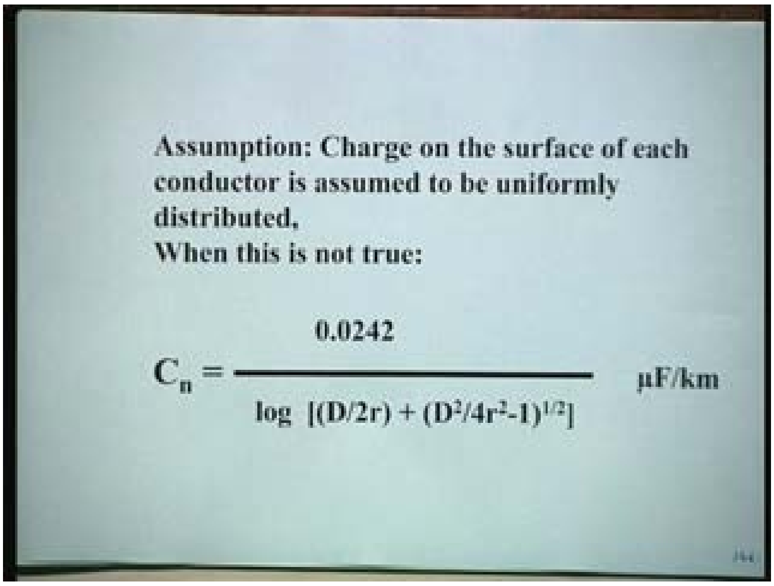

What are the assumptions in deriving these equations which you might have derived in your earlier courses; charge on the surface of the each conductor is assumed to be uniformly distributed, any assumption in life is not necessarily, in fact not 100 percent true right, it is only an assumption, an assumption is something which is close to what happens in practice. IT students always study, it is an assumption, but it normally happens, I mean most of the students will study, IT teachers take classes, they do take classes, there are some who may not take classes, but that should be minority, if it is majority, then this assumption is invalid.

If it is not true, suppose it is not uniformly distributed, then formula gets modified to this one and now it is bit slightly complicated d upon 2 r gets modified to d squared upon 4 r square minus 1, under which again microfarad per kilometer. There are some examples given in the book based on this non uniformity of distribution of charges on the surface of conductor and see what difference does it make in computation of capacitance and that will give you a fairly good idea, how much affect is there of charge being not uniformly distributed. In fact, not much and that is why we neglect that, if charge distribution is not uniform, we do not take any cognizance and we can continue to use this formula, but if somebody is fuzzy, here is another formula and that he can compute it exactly.

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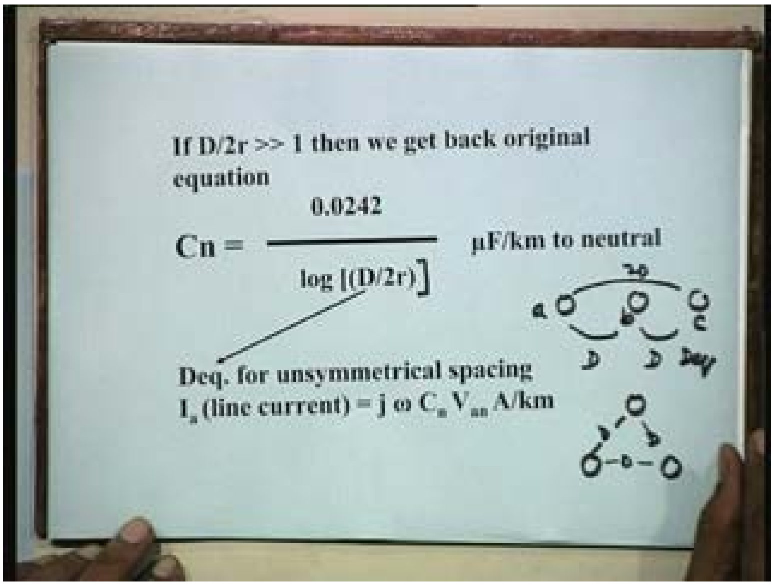

I said if D by 2 r is more than 1, which is normally the situation spacing is always more than the diameter of the conductor or wire, in that case we get back our original equation log of D upon 2 r macrofarad per kilometer to neutral, these should be replace by d equivalent for unsymmetrical spacing; please understand unsymmetrical spacing is something different than non uniform charge distribution. Here, it means this is unsymmetrical, do not think this is symmetrical why between a and c, it is 2 d between a and b, it is d between b and c it is d, though it may look you symmetrically placed, but it is not symmetrically spaced.

This is however symmetrical spacing, because each is d, so here you use d equivalent which happens to be incidentally cube root of d into d into 2 d; so 2 d q whereas, here d equivalent is same as d, because d equivalent is nothing but, d q and cube root of which d again, so line current is equal to j omega c n, v a n ampere per kilometer c n is this the formula to be used for c n, v a n is known to you well here is the big figure.

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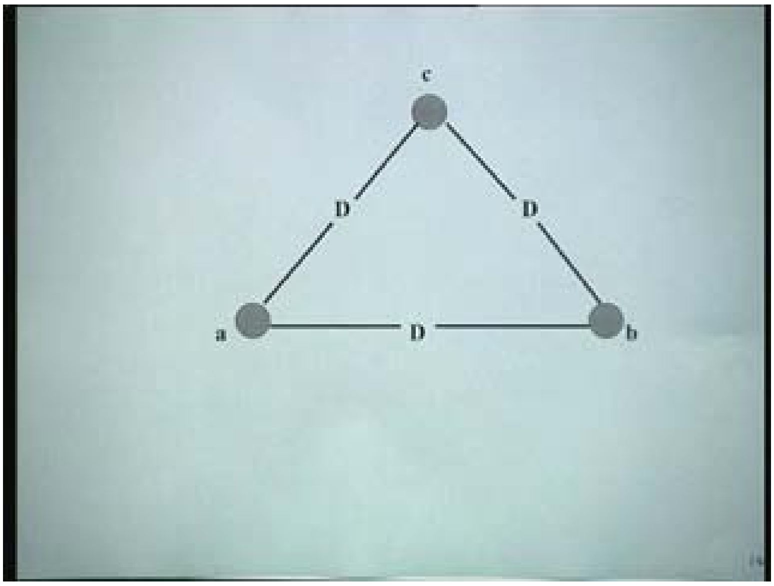

Shown to you, which I have already drawn, there was no need to draw, but still since it has been drawn, you can have a look at it; these are the three conductors a b c and this is the equilateral triangle, they are sitting on the vertices of an equilateral triangle, an equilateral triangle is one whose sides are equal.

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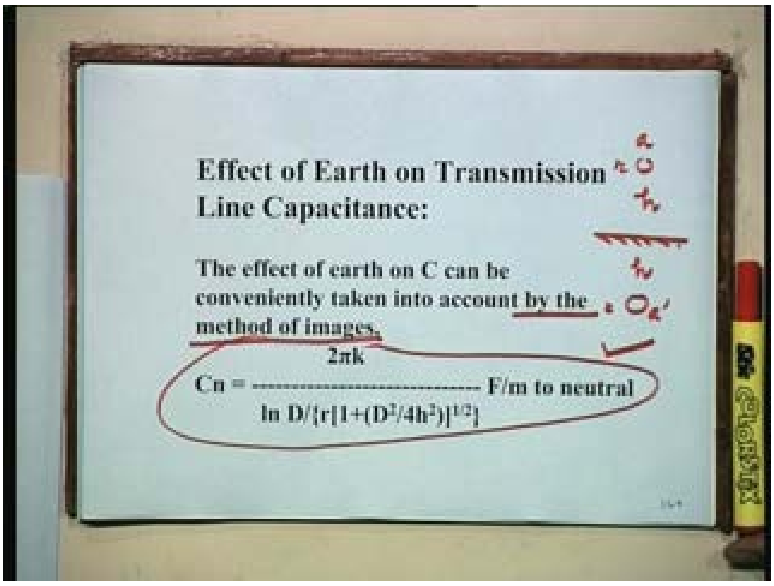

This is a very important topic in capacitance as I told you earlier, this is not effective in conductance, the effect of earth on transmission line capacitance; why you to bother for effect of earth because, capacitance in the shunt parameter it is ground it whereas, inductance is not a shunt parameter it is a series parameter, so we highly care for earth presence we ignore as it is the lines are quite high from the earth, so the effect of earth on capacitance can be conveniently taken into account by the method of images. I am sure those of you have studied a field theory in your under graduate, they must be knowing what is method of images, those you know optics they should also know what is method of images, now the equation can be derived when you consider the effect of earth, this is the method of image, this is a conductor, this is a earth, this is height, height this is r a dash and then, they can be specifying D b dash c dash and so on.

So, effect of earth and capacitance can be conveniently taken into account by the method of images and the formula, so derived is this 2 pi k log d upon r 1 plus D square upon 4 H square whole thing under root; so, many farads per meter to neutral please remember here, there is no microfarad per kilometer, here it is farad per meter. You can solve a numerical problem involving the effect of earth and see how much difference it makes, at least go through these solved examples, of please do not worry about unsolved.

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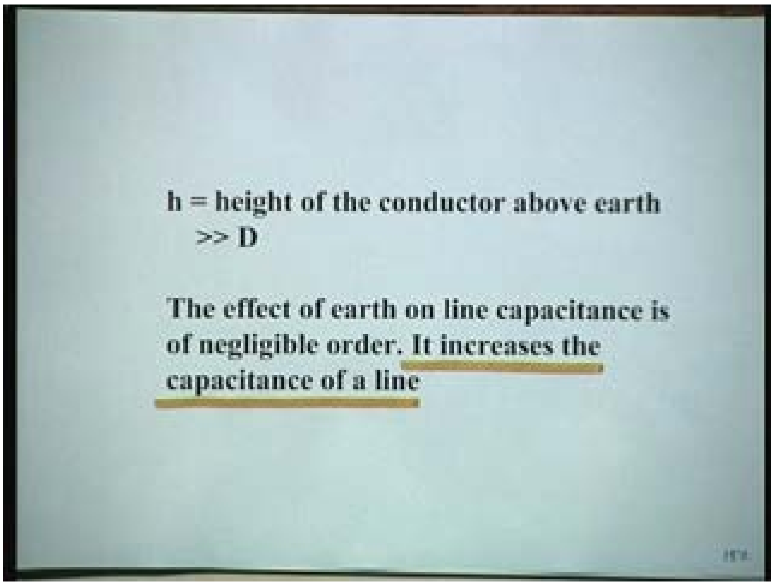

At least solve the solved examples of chapters two and three and four that should be enough as for as this course; is concerned height of the conductor above the earth is much much more than d the effect of earth on line capacitance is of negligible order, inductance anyway it is neglected but capacitance also it is negligible, but what happens if you want to consider it increases the capacitance of line, this is asked in interviews.

Teacher may ask you in interview, do not worry I want to include it, you may say no no sir it is negligible, it is no no its still I want to what happens and suppose you say decrease the capacitance and your chances of becoming also decreased, you have to say it increases the capacitance of a line. That is clear from the formula itself you do not have to apply much brain, why it increases the formula itself tells.

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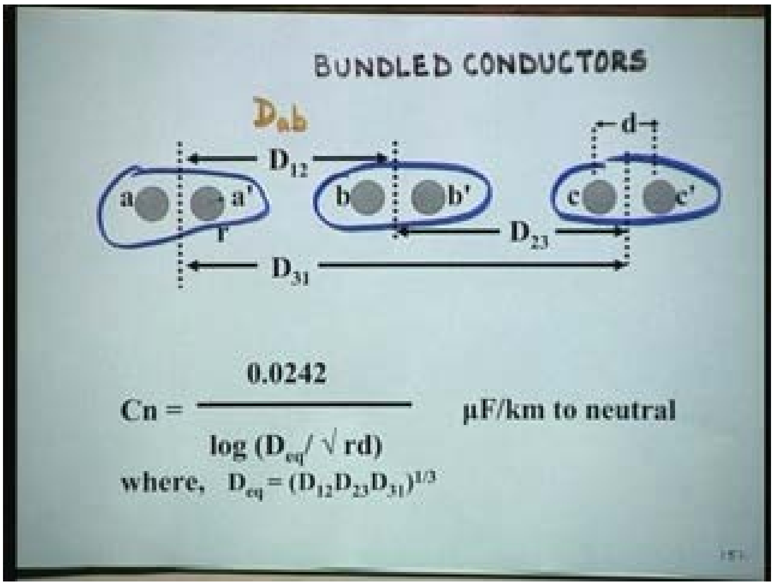

We have done bundle conductors in inductance, having same thing you have to do in in capacitance for similar reasons, you also want to reduce capacitance, why we want to reduce capacitance; anything which reduces the voltage it has the voltage drop should be reduced. So, here now you have shown a bundle of two sub conductors: this is phase a, this is phase b, this is phase c, the sub conductors are from each other at a distance small d and the whole phase a is D 12 from phase b, D 23 from phase c, and d 31 from between phase a and c.

Naturally, it is unsymmetrical spacing, even D 12 did not be same as D 23 that is why it is not only D, I further made substitutes 12 23 two 31, which incidentally also tells you it is from conductor 1 and 2, conductor 2 and 3 or alternately you could have ask me why we not use a and b, right you could have very well use D a b, no harm D b c, D c a same thing it already makes some difference and now the equations are for capacitance 0.242 upon log of D equivalent upon under root r, D what is under root r D s self g m D, right and D equivalent you know already which is the cube root of all three spaces multiplication of all three spaces with this, ladies and gentleman we finish chapter three and we start chapter four which is called representation of power system components. In fact, we are reviewing what we have done earlier; this is representation of power system components.

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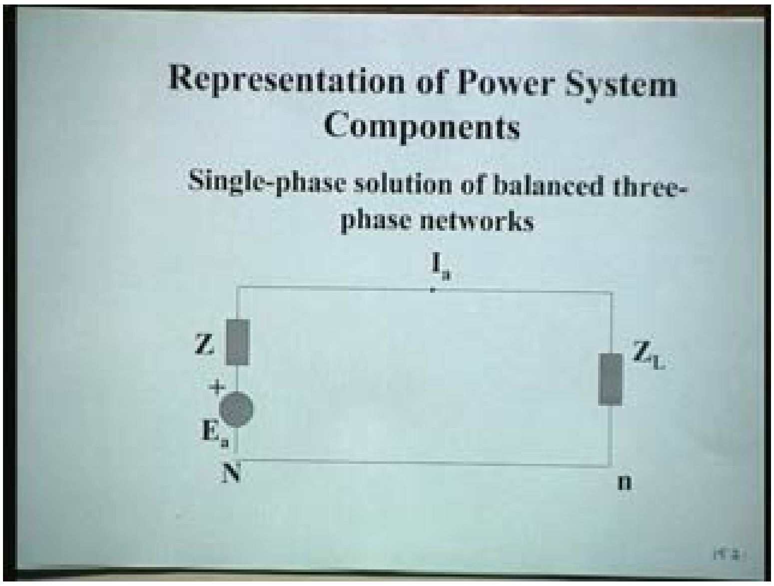

What you shown in the figure is single phase solution of balanced three phase networks and if the networks are balanced why shown all three phases, it is a replica of three spaces, only difference of 120 degrees field difference. So, go on subtracting or adding 120 degree depending on which phase you are consider, what you shown in the figure is a single phase of balanced three phase networks, this is source, this is a impedance, source impedance, this is a load impedance, this is neutral of the generator, this is neutral of the load n is connected. Now, there are one lined presentation of simple power system, line diagram call it this is used in practice because, actual diagrams are very complicated, so for simplicity, for easiness, for understanding, we use line diagram or one lined presentation of a simple power system.

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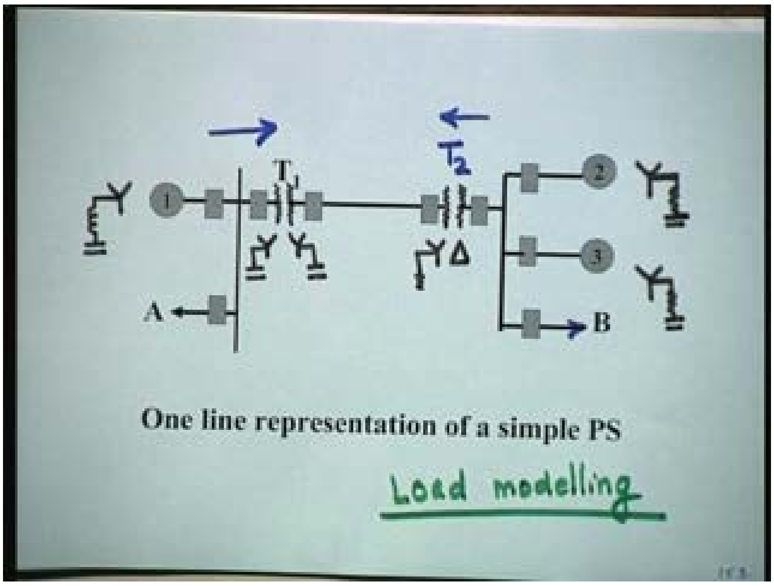

This contains practically everything that is there in a power system, it has shown generator on both the side, receiving end as well as sending end, that is why now there is no use of calling sending and receiving end, you can send from any end power, you can receive power to any end node; for simplicity we are calling here generator one, generator two, generator three, there are only three generators now, it is a star connected grounded through an inductance, all three generators are star connected, but some of are grounded through resistance, some of them grounded through inductance.

So, grounding itself is a big factor in power system, I am sure you must all have done it in your under graduate; what is what is all these things you can review, you can go through in that red book or brown book whatever book it is, there is a chapter given there on lightning and on insulation insulation coordination, trangium card all these things you can read if you want to revise, then there has to be a transformer T1 T2; obviously, the generator and transformer has to be step up, if power is going from here to here, if power is going from here to here, then this has to be step up, whichever side you have sending power has to weak because power has to sent at a higher voltage, it is cheaper, higher the voltage more power transfer is possible now, transformer is also star delta delta star you may see a table given in book a 30 degree you know, what is the shift in the phase, shift all those things. So, here it is star star solidly grounded here, this is star delta, star grounded delta is, there is no question of delta having in ground then, this rectangles are circuit breakers this is a load a is a load load can be on both the sides, let power can be generated can be in both the sides. So, is the load, two loads are shown in this figure; load a load b and as we already know load can be represented in three manners load modeling: in fact, load modeling is a very important chapter in power systems why because load itself is a very important parameter, if there have been no load there have been no electrical engineering therefore, nothing to supply power, why should we study power systems, we are studying power systems because, each and every time we needs electric power, whether it is your computers, whether it is your hair driers, whether it is your geezer or a c or fridge or vacuum cleaner; whatever device we use it has the motor may be tinny motor, may be big motor, may be small motor and that motor has to run from electricity, the input is electric power, output is mechanical power.

So, it runs whatever you want to run whether it is a mixie, whether it is (()) whatever or a big gigantic industries, circuit breakers why do you need you want protection, you want to protect your system, why do you wear sweater in winter? may be you want to protect your body from cold, from wintry winds; why do you wear a hat or a cap or a in summer because, we want to protect your eyes, protect your body and now it is all sorts of sun creams are available. As if you are became sports person and you have to stay in a sun long hours, so use those sun creams on your exposed part of your body, in fact this is real danger of getting skin cancer, in countries like Australia, where sun is very very strong even 35 degree centigrade is often there, so it is injurious, so for 35 degree is nothing, we are 2 into 48 45 46 35 is fair good weather for us, for them it is certifies very bad, this year in France several hundred people died, because of the sun stroke, because of the hot sun, for the first time 100 degree Fahrenheit is crossed it made a history, for us every day hundred Fahrenheit or 95 Fahrenheit is crossed; so, this circuit breakers are required to protect the various devices, various generators, loads, transformers.

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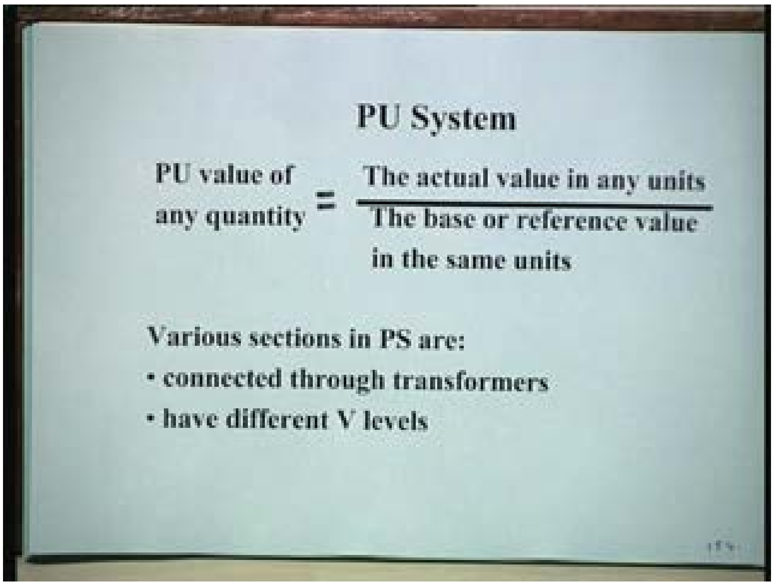

So, which is shown in a rectangular form, what is a per unit system? Not Punjab university, PU is per unit, I am sure all of you know what is per unit, you cannot pass your degree exams without knowing what is per unit. Electrical engineers per unit value of any quantity is equal to the actual units, in any units upon the base or the reference value in the same units units have gone to be same in numerator and denominator, because per unit value has no units, so units have got to be cancelled, so you convert the one of the two units are not same, various section in power systems are connected through transformers, I was just talking about why they are connected to transformers and since they are connected through transformers.

So, they have different voltage levels, because the mere presence of transformer allows you to have a different voltage level on both sides, because the transformer is serving that purpose to interconnect two sections having different voltages, same job is done by frequency converter if you to interconnect France and England, where two frequencies are not same. Let us start with impedance, because as I said load is the main thing, impedance per unit impendence is obtained by impedance in actual ohm into base upon k V base whole square, which derivation of formula is given in the book if you want you can go through the derivation otherwise, you can assume it on any case you can done it in earlier courses.

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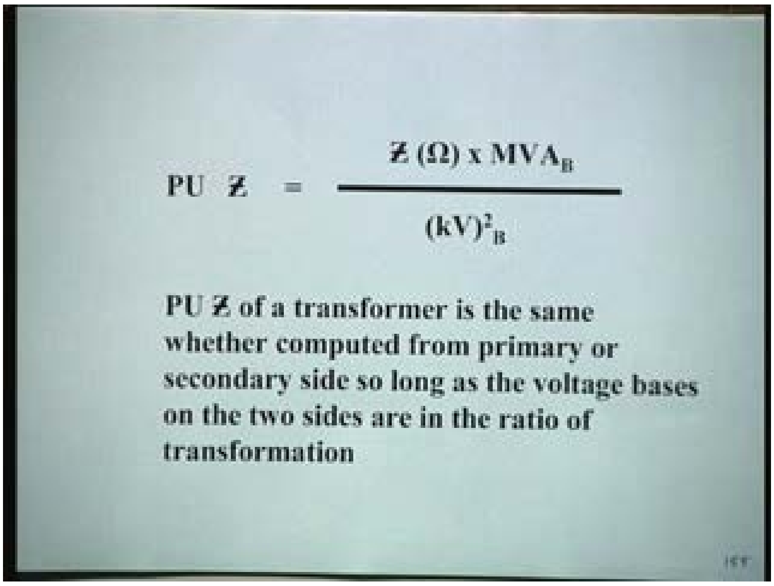

Per unit transformer sorry per unit impedance of a transformer is a same whether computed from primary or secondary side, so long as the voltage bases of the two sides are in the ratio of transformation, suppose it is irrelevant to 33 KV transformer, the transformer ratio is the small a is one by three or three depending on which you are looking at, so if your bases are also in the proportion to 1 is to 3 or 3 is to 1, then it hardly matters whether you are computed from primary side or from the secondary side, the value of per unit impedance of a transformer will remain the same.

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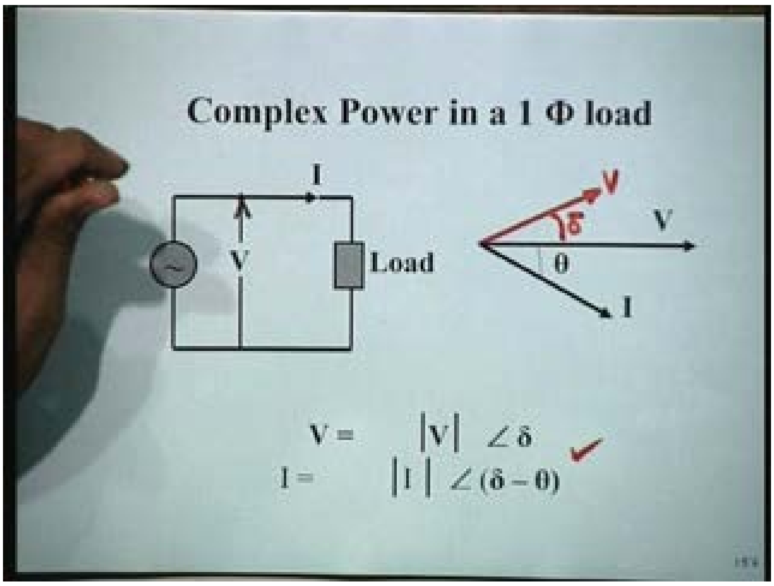

You can read more about per unit things into the book chapter four and you can see how a base is change, the per unit value changes, you must have given that per unit value of new base is equal to per unit value of the old base is equal to KV base old upon K V base new whole square into I V base old upon I V base new this formula is known to you, so I have not written it here, please revise it. What is the complex power in a single phase load, the different types of power complex power, real power, active power, reactive power, apparent power and so on, here is a generator shown in a power, having voltage V across it current is I and here is a load, we cannot get simple power system than this it is a power system, they has to be source, they has to be a load voltage and current and anything else and the phase diagram is a simplest type of pharos diagram; voltage is a reference most of the time and current is lagging because 99 percent of loads in practice are lagging load, why it is a induction motor, which forms the main part of the load right from fractional kilowatt to several hundred megawatt. So, for induction motors, so all induction motors have lagging power factor, so the current is lagging voltage by theta, theta is the power factor angle, theta can vary from zero to infinity, so the voltage shown or voltage phasor is equal to voltage magnitude into angle delta and current is I into angle delta minus theta, here delta is zero suppose if there is a some crack (( )).

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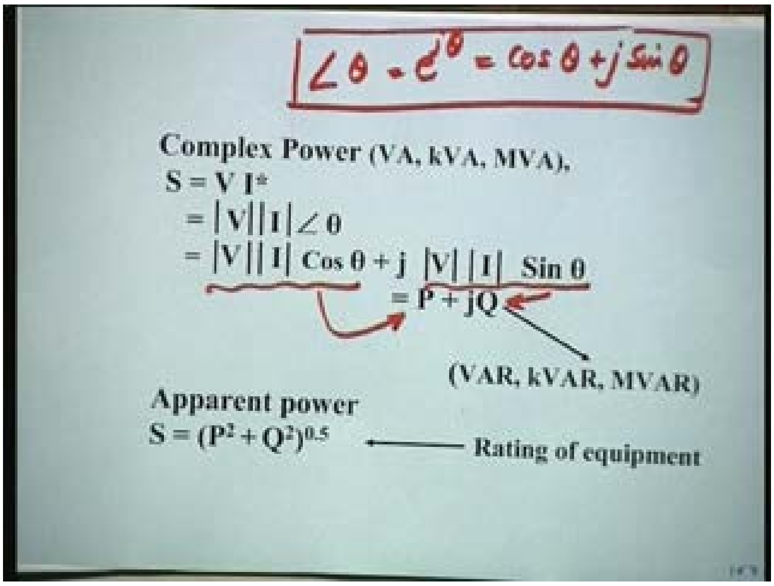

So, in that case it is true, what is complex power? I just talking about complex power as is V into I conjugate, why it is complex because of the conjugation phasor quantities are there there is a magnitude as well as angle referring to the last phasor diagram shown to you. Just now, units of complex powers are volt amperes KVA, MVA that solve we do not go into milli volt ampere, that is a job of electronic engineers, communication engineers, they go in a different part of the frequency megahertz, gigahertz we operate in the just 50, 60, 0 to 100 mega power, but not frequency, so I was magnitude I angle minus theta in that figure. So, you conjugate it to make it plus theta, a plus j b conjugate will be a minus j b, what is conjugate? Change the sine of imaginary parts, if it is a minus j b, it will became a plus j b, if it is a plus j b it becomes a minus j b, so here it becomes I angle theta it was actually I angle minus theta, because theta was lagging if I expand it further I hope all of you know they are all same, I hope you know these all three are same is it cleared all of you, all these three things are exactly same.

So, angle theta can replaced by cosine theta plus j sine theta and V I is a common factor to both and all of you know that, V I cosine theta is nothing, but real power real sine theta is reactive power. The units of real power is watt, kilowatt, megawatt, gigawatt, nowadays we have talk of and simultaneously, the correspondingly the units of reactive power is VAR kVAR MVAR GVAR and what is apparent power any one of you, the magnitude of complex power is called apparent power, however the units remains same, so p square plus q square under root is apparent power. What is this apparent power? The rating of various equipments is always shown in kVA, MVA, VA, the transformer of a generator of 10 kVA, so equipment rating is always showed in apparent power, if q is positive it is a lagging current, lagging power factor, if q is negative it is a current leading, power factor.

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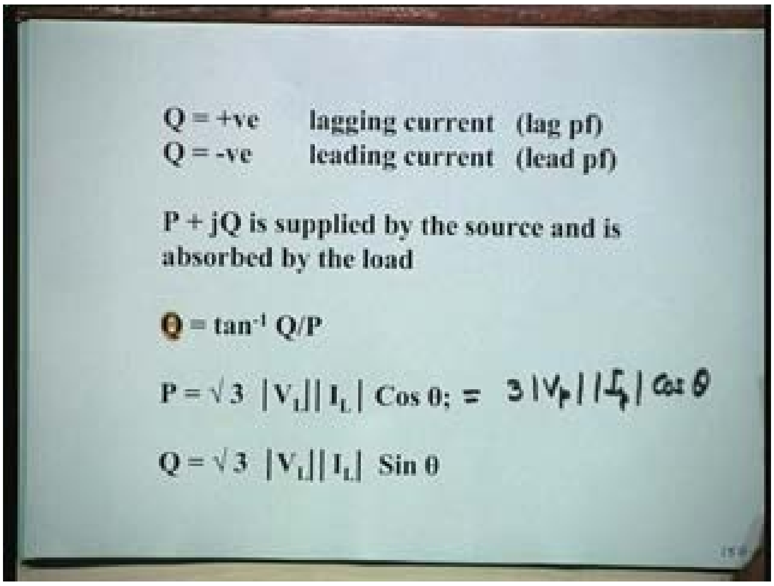

P plus j Q is supplied by source and is absorbed by the load, source and sink in electronics you might have read source and sink, Q is nothing but tan inverse Q by P is it Q, so V theta, that is a problem if somebody else types and somebody else gives lecture, two should be same right. So, P is root 3 v l I l cosine theta if you want to use line values which is nothing, but same as three times V phase, I phase into cosine theta, because is as line the others becomes line upon root three, so root 3 gets cancelled and 1 root 3 is left. So, they are same same thing I can do here also and I am sure you must remember this equations, till your electrical engineering, once you will became city bank then no need, to it all of you starts selling cigarettes, then no need to do it.

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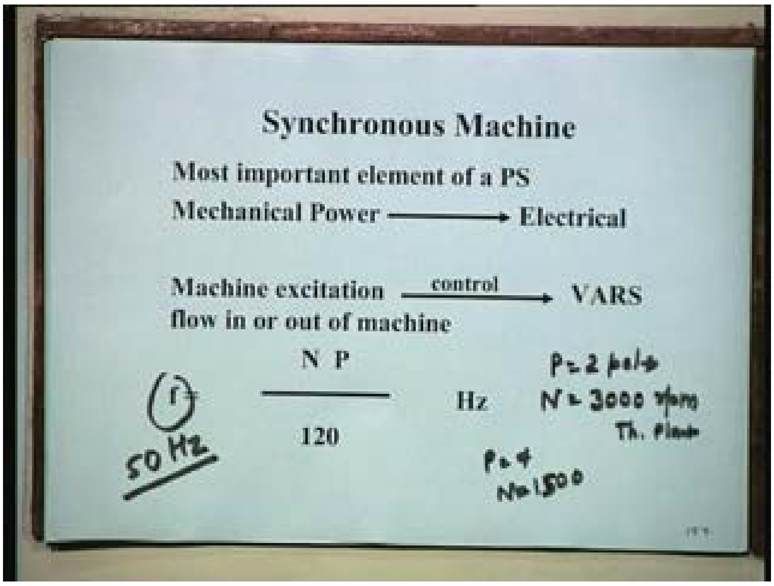

Synchronous machine, I am sure no past engineer can forget about synchronous machine as you cannot forget about induction machine, in fact induction machine is also used as a generator, when you use non conventional sources of energy that is what yours main topic most important element of a power system is synchronous machine, because a synchronous machine is not there there is no power generation and if power is not generated we do not need any induction motor whose to supply power to them.

So, mechanical power gets converted into electrical power in synchronous machine, the input is mechanical, the output is electrical, in motor input is electrical, output is mechanical; just the reverse, otherwise machine same, machine excitation control vars flow in or out of machine, the equation for frequency is well known to you NP by 120 N is the speed P is the number of poles 120 is 120000 plus 20 hertz, if you want a two pole machine the f is since the value of f is known, so for a 50 hertz supply for P is equal to two pole, the N is 3000 RPM which normally required for thermal plant, if P is four N is 500 1550 750 and so on. Similarly, if get 60 hertz when you get employed in U S then this 3000 will change to 3000 will change 36000 and 1500 to 1800 and so on.

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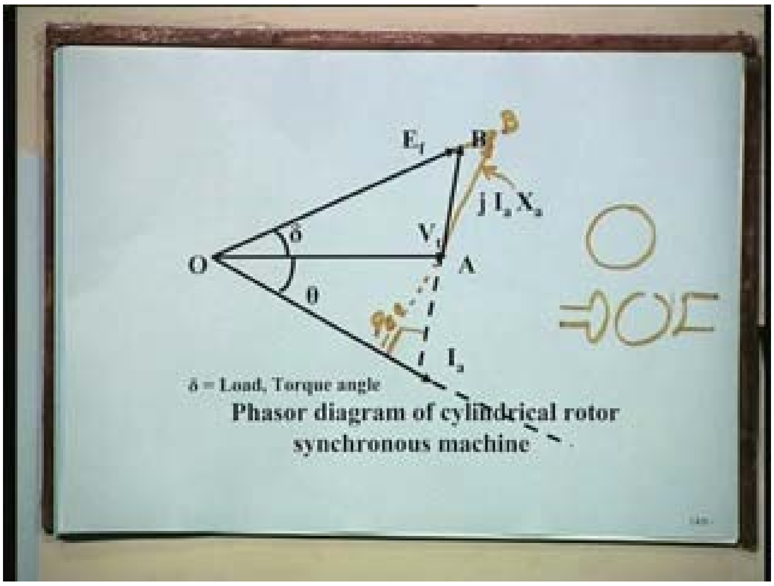

This Phasor diagram is very important, E is the excitation voltage, V is the voltage at the machine terminal, this is a current lagging by theta, if you add to this voltage the drop, that you get excitation E f, delta is called load angle, torque angle and so on. Theta is the power factor Q by P, this is a current actually the figure is not drawn properly, this is 90 degree because all drops are added 90 degrees, so this should have been, this is b, right this is phasor diagram of cylindrical rotor synchronous machine, why cylindrical? Anybody because it is only X otherwise, you would have A X D and X Q 2 reaction theory this is non non (()) is cylindrical otherwise, it would have been like this, where the air gap is non uniform.

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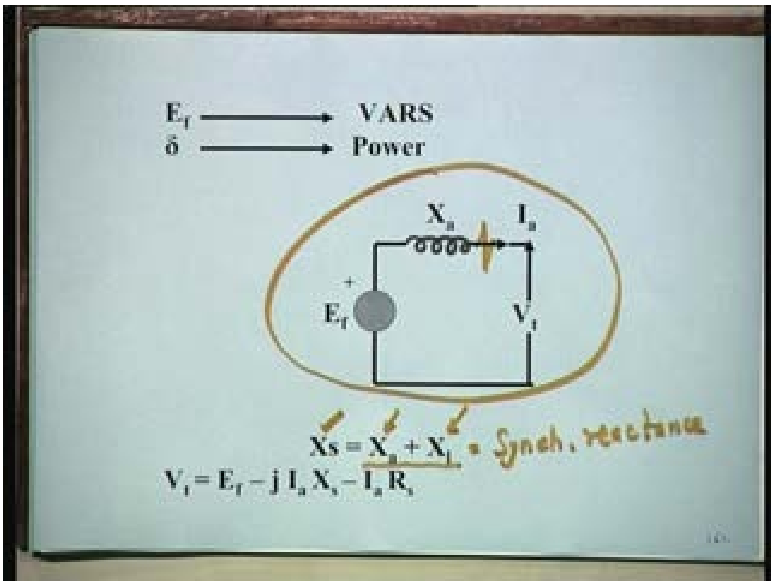

E excitation voltage is something do with VARS, delta has something do with power, real power, this is a simplest possible, representation of a synchronous machine, constant voltage with constant series reactance and terminal voltage and current. This X s is nothing, but X a plus X l armature reactance and leakage reactance, both together are called synchronous reactance; so V t can be written as the E f minus a drop, the resistance as well as inductance, you can always have resistance in real life. Even your inductance will have a some resistance, it may not be perfect inductance, it may be leaking; anybody who knows what is infinite bus? Very good it is like a sea, if you take a one bucket of water from sea nothing is going to happen.

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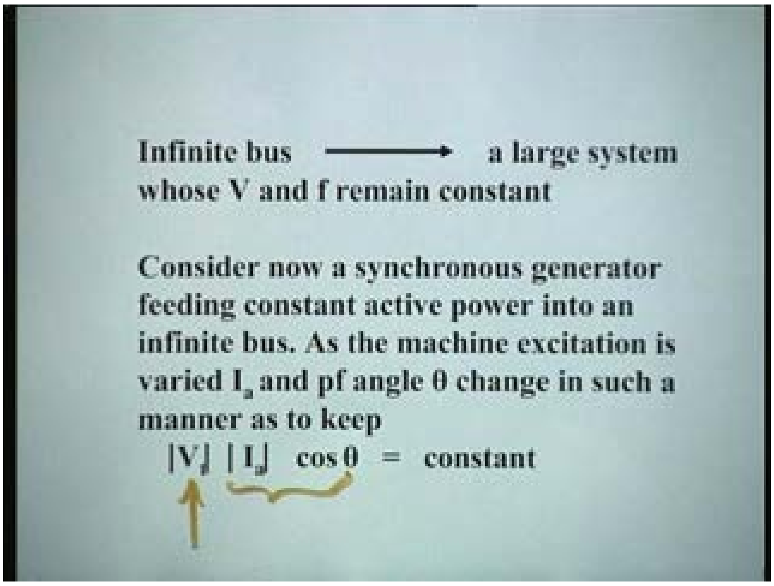

So, a big system its voltage and frequency remains constant, even if you draw power factor exact analogy is like a sea. So, large system whose voltage and frequency change it is called infinite bus, is normally asked in interviews again. Consider now a synchronous generator, feeding constant active power into an infinite bus as the machine excitation is varied current and power factor angle also change in such a manner as to keep the real power constant, this is a subject of our next lecture that is tomorrow. Why this is important? without affecting the real power flow, we can play with, temper with, the power factor angle as well as current, because the one changes the another has to change because the total this remains constant, since you are keeping v constant, these two have to change in different direction, so that the product remains same, so this story we will be learnt, narrate, listen, tomorrow that is tuesday, so today any difficulties, so far.

What is load modeling?

Load modeling is our last section in this chapter, load is the normally modeled in three ways: the constant impedance, the constant admittance, constant current and constant power, you must have rate the numerical as five NPMA load of five mega watt a load of five ohm. So, how the load is modeled, depending on which studies you are doing if you doing load flow study load is always specified as megawatt in India P and Q if you are doing relaying protection, load are five amperes and otherwise, normally you have load in ohms impedance, constant impedance, constant admittance, and then, there are complicated loads modeling where it varies with voltage the voltage varies load varies and there are several other models. In fact, you can do p h d thesis on load modeling. So, that I think we will wait until your break is over anything else.

So, why the communication lines are run parallel to the power?

As I told you earlier days to save money of the towers or poles, because otherwise you have to erect another pole, where is the where is the space, why transmission lines you are not able to erect the right of way, each inch of space in Kerala, if you have to go to Kerala either there is a water or there is a irrigation or there is a house, there is no space are available. Soon, we will have same problem in I T campus where do you erect, new hostels, where do you built houses for employees, faculty we each each is going to be used we have to have playgrounds, we have to have administration building, we have to have teaching blocks, we can go only vertically because there is no space and that is why we have using the same poles same tower, so otherwise go for wireless communication.

It is having drawbacks too

There are always plus and minus in life, we cannot have any arrangement where there are no drawbacks, where there are always pluses, win win situation we do talk, but there is situation which has been win somebody else must be looser in that will will right anything else.