Power System Operations and Control
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Module - 02
Lecture - 03

Welcome to lecture number three of module two that is equipment and stability constraints in power system operation. In last time, we saw that the various types of generators in terms of their construction means we can use the cylindrical rotary machine alternators for this turbo thermal power generators and salient pole type of synchronous generators for a hydropower generators. Again due to the technical reasons that is turbines steam turbines are very very efficient at the high speed. So, we go for the minimum number of poles that is pole is equal to two, and hydro turbines are technically efficient if they are going for the lower speed.

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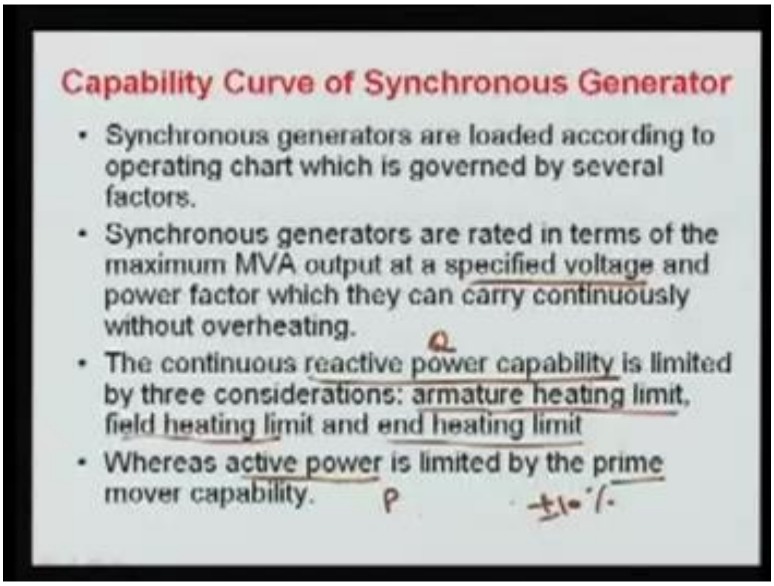

Today, we will see what is the capability curve of a synchronous generator, and that is true for whether it is a salient pole or it is a cylindrical rotor synchronous generator. Synchronous generators are loaded according to the operating chart which is governed by the several factors. The factors normally is that we cannot increase the voltage; the voltage is also is limited constraints and as well also the loading of the real and reactive powers also means we have to limit, and the generator must operate within certain region.

If you see the rating of the synchronous generators, they normally rated in terms of voltage, power and if you are using the apparent power that is MVA, then it will be with the power factor. In some of the generators, normally we say 200 megawatt generator. It shows that this real power that is maximum real power we will see what is the rating of a particular generator. There is some point where we normally specify. If you are using MVA, then it will be associated with the power factor and of course the specified voltage as well.

Means at this rating, the generator can continuously run without overheating of all these instruments, and it should not interrupt. And it should not violate various operating limits of the synchronous generator. The continuous reactive power capability that is reactive power capability is limited by three considerations, and all these three are basically the heating limits. First one is your armature heating limit; second is your field heating limit, and third is your end heating limit.

Armature heating limit basically associated with the current which is flowing in the armature winding. There is some current in the armature winding once this generator is generating power. So, due to the resistance of armature winding, there will be I^2R loss and thus that heating that energy which is associated with I^2R that is must be dissipated. And if it is not taken away and again it depends upon the cooling of the system, then there will be raise in temperature and that temperature may damage the insulation of the winding of your generator.

We know this synchronous machine; they are doubly excited means we have the DC field in the A field winding. We are providing the DC current, and of course, that will have some resistance. So, the field current square into the resistance, there will be some loss, and that loss is basically giving your field heating and then it is also limited by the field heating limits. End heating is basically related with the flux. There is some flux in the machine that is more and there will be more basically flux and more eddy currents and there will be more losses. So, the three heating limits basically give the capability curve of synchronous generator.

The active power that is P and this is your reactive power Q. So, the active power is basically limited by the prime mover capability. Normally, the overloading capability of the turbines is very very limited; this is a mechanical device. Normally, if you are going for more power load capability of the turbine, the cost of the turbine is very very high. So, that turbine capability normally it is not more than $\pm 10\%$ of its rating. If you are going for more, of course, here that the cost of whole your generating system will be very very high.

So, the generator even though they can go more power overrating means they can generate more power or particular even for the particular duration, but due to that turbines that is a prime number turbine limitation, we cannot generate the overrated power for the longer duration. Now let us see all these three limits for the reactive power. So, the reactive power is limited by the turbine capability; also we have one constraint that is your voltage constraints and that is limited by the insulation of the winding.

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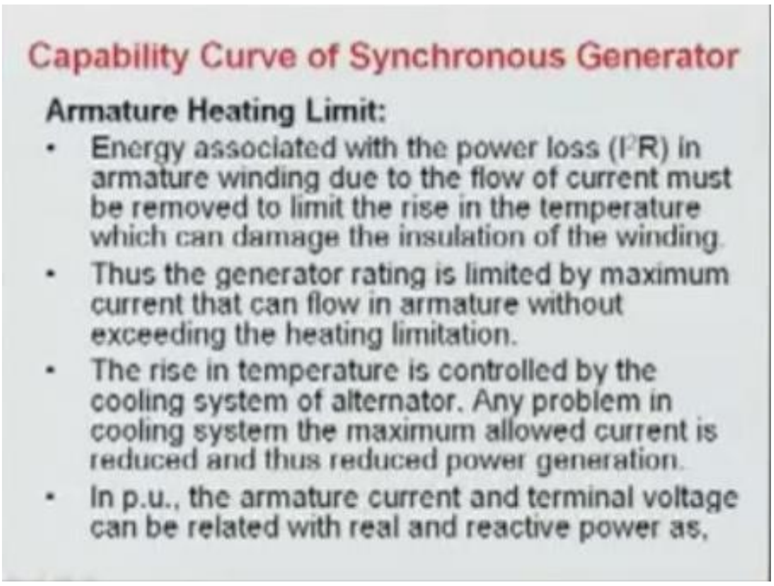

So, the third constraint that is on your reactive power that can be again analyzed and we will see the capability curve of our synchronous generator. Let us first see the armature heating limit. The energy associated with the power loss I^2R in armature winding due to the flow of current must be removed to limit the raise in the temperature which can damage the insulation of the winding. So, whatever the loss Due to this I^2R is occurring in generator that must be taken away; otherwise, what will happen? There will be raise in the temperature.

And once there will be raise in temperature, there will be possibility of the damage of winding insulator and we do not want. So, since, we have a fix cooling system, it has some limitations as well in the cooling system that it will carry; it will take the heat generated inside this synchronous generator that will be taken away. It has some limitations, and that depends on the cooling of your system. Thus generator rating system is limited by the maximum current that can flow in the armature without exceeding the heating limitations.

The raise in temperature is controlled by the cooling system of alternator. As I said any problem in the cooling system, the maximum allowed current is reduced and thus reduced power generation. Suppose, cooling system is failed or it is not properly cooled, then you cannot load your generator to its rated value. You have to operate your generator at the reduced rate if your cooling state is not perfect. In per unit, the armature current and the terminal voltage can be related with the real and reactive power with this equation.

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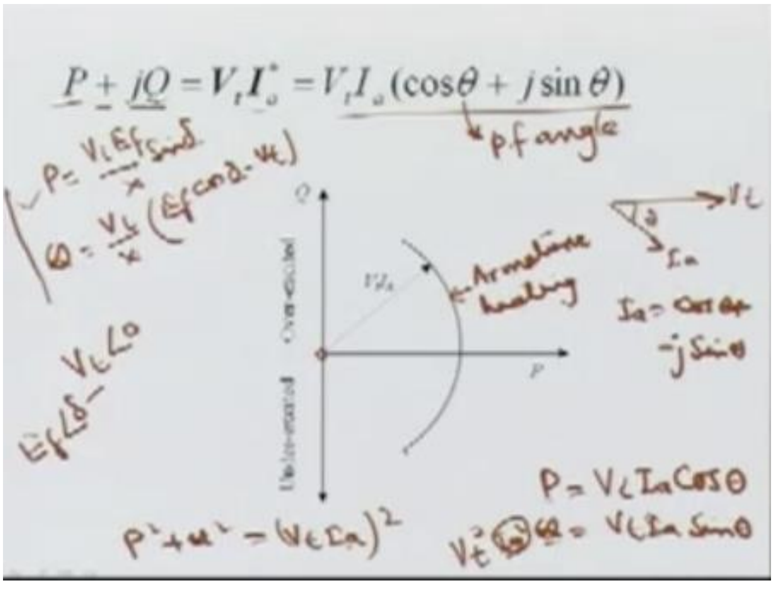

That is a real power P plus here your j of reactive power, P +jQ $= V_t I_a^*$ that can be written at your Vt the terminal voltage and the current that is flowing. Here I express this equation even though on previous term as well and we derive for a synchronous machine here P; that is $P = \frac{E_f V_t}{X} \sin\delta$ and also the Q, I express here $Q = \frac{V_t}{X}(E_f \cos\delta - V_t)$. So, it was in terms of here, the δ that was the phase angle or you can say the load angle because it is an angle difference between Ef and the Vt.

Now here what we are going to represent in terms of the power factor angle; this θ is your power factor PF angle. So, we can write here if this is a conjugate. So, we can take the Vt as a reference, then there will be angle here, suppose your Vt here; this is your terminal voltage, and this is your current Ia, and this is your angle θ that is your power factor angle. So, this we can take here the cosine component and thus your sine component and we can write here this component as this one. Means I can write the vector Ia with your cosine θ plus here sorry it is minus because it lagging let us suppose then it is sine here θ.

Since we are taking the conjugate, so it will be positive and then we can write with this expression. Now if we will see this expression and we can separate out real and reactive term, then I can write here this real power will be your Vt Ia, and it is your cosine θ. However, Q is nothing but your Vt Ia sine θ. In the previous here equation, it is also for real and reactive power that is injecting at the terminal voltage of this synchronous generator. It is in terms of your δ that is your voltage angle, here what we took? We took Vt angle zero and your Ef was your angle δ and then we derived the expressions.

Here we are deriving in terms of θ. So, our intention is to draw a curve between your armatures current because that is our primary objective; here there is no armature current. It is in excitation voltage as well as your terminal voltage. Now if you will square and add these two equations, you will get here this $P^2 + Q^2$ and now you are getting Vt Ia of whole square. Now this equation is an equation of a circle. So, we can draw a characteristic like here; you can see here this is your equation of circle and its origin will be here zero and this is your radius.

It will be nothing but your Vt Ia and this is a curve as would this limit is called your armature heating limit, because we cannot exceed this value, because it has some limitation, because I here for fixed terminal voltage, I cannot be more than certain value. So, with this heating means we have to fix I in such a way because Vt is specified; that is fixed terminal voltage. So, what we are getting here V_t^2 into I_a^2 and you know this is the directly proportional to the heat that is I^2R. So, I square here is directly related. So, we cannot increase this current due to the heating, and this is due to the armature heating limit.

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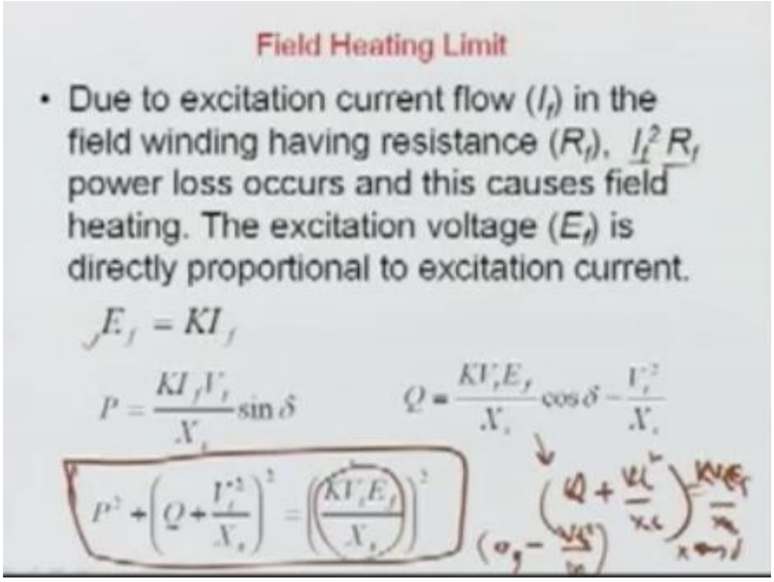

Now let us see the field heating limit. Due to the excitation current flows If in the field winding having resistance Rf I^2 here I square of the field current multiplied by your field resistance power loss occurs and this causes field heating. The excitation voltage Ef is directly proportional to the excitation current. So, we can write here Ef is equal to K times field current. So, now the equation which we derived earlier that is P if we will see here; this P is equal to $P = \frac{E_f V_t}{X} \sin\delta$, and Q is equal to $Q = \frac{V_t}{X}(E_f \cos\delta - V_t)$. And putting this Ef value is equal to K If, we will get this expression.

Similarly, also we can get for Q is equal to K Vt Ef like here this equation. Now here we want to remove this δ and then we will get expression here means this expression we can write this $Q + \frac{V_t^2}{X_s}$ and that will be equal to your here $\frac{KV_t E_f}{X_s}$ and again it is multiplied by cos δ . And if you are squaring and adding, then we will get this expression here, and once again, you can see this is an equation. This is an equation of a circle where your origin is your or this is zero and $\frac{-V_t^2}{X_s}$is the origin and your radius will be this component.

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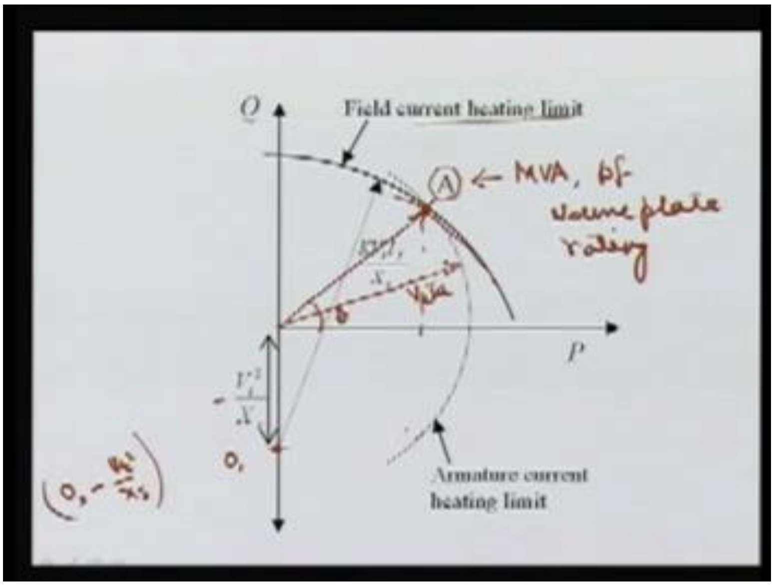

So, if we will draw again the circle corresponding to this, you will get a curve like this; means this was your due to this dotted curve, it was a circle here, and it was related to this if you remember here it is Vt Ia. Now due to the field heating limit, we say that here the origin of this field current equation, here it is your zero and this is your minus value. So, we are getting this is your origin here. So, P is 0 at this point, but the Q we are having this; means you are the origin of this circle starts here that is your $(0, \frac{-V_t^2}{X_s})$ here we are getting this. And the radius here as I explained K Vt If axis and if you will draw, then this is here; this is a circle.

Now I had a point here a both curves that is an armature current heating limit and the field heating limits, they are intersecting at the point A, and basically, this is the name plate rating of synchronous generator. So, the point here we say what is the power factor; now this is your power factor. So, I say this is a theta. So, at this point, we say what is your power or MVA and then we have to write the power factor. So, we can write the rating here is your MVA and power factor at this point is your name plate rating we call; that is your name plate rating. So, we have now means now our characteristic is now operating characteristic here and after that it will follow the lower section here.

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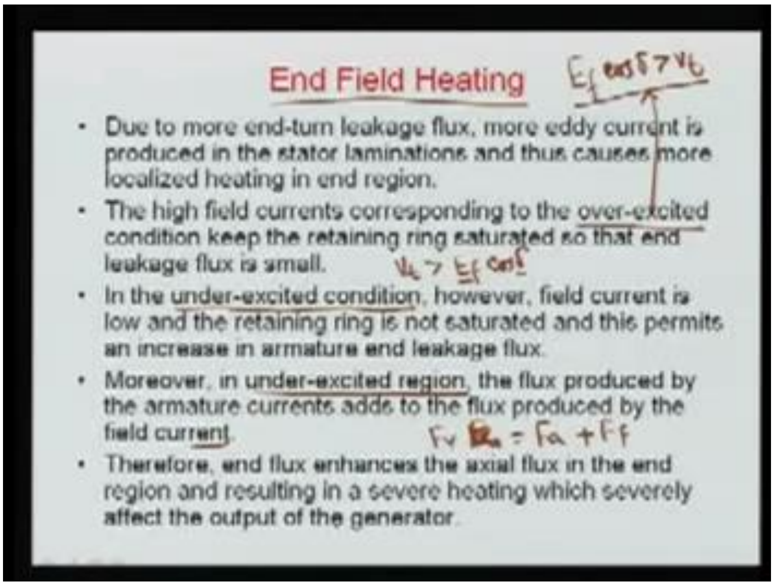

Now let us see another heating limit that is called your end field heating limit. Due to the more end-turn leakage flux, more eddy current is produced in the stator laminations and thus causes more localized heating in end regions. The field current means the high field corresponding to overexcited condition keeps the retaining rings saturated so that end leakage flux is small means during the overexcited. Now what is overexcited? In overexcited, it is nothing but if you remember I said here Ef cos δ is greater than your Vt. This is the case of synchronous generator; however in motor, it is the reverse here means Ef cos δ should be less than terminal voltage, then it is called overexcited in the motor operation.

Since, here we are talking about the synchronous generator. So, the overexcited means here this condition is satisfied. In that condition, the end rings normally they get saturated, and the leakage flux is a small. So, there is no heating problem in this due to the end field heating; in under excited that is one of the conditions where we have to think what will be the field flux. The field current is low; at that time, field current in the under excited is low because this value is less. Means for the under excited here this Vt is more than Ef cos δ ; what does it mean? Under excited, this Ef is less, because this δ decides the power which you are injecting that is a real power.

So, this Ef is less means If is less and If is less as I said, the field current is less. Thus retaining rings is not saturated; this permits an increase in armature end flux field. And it is more armature flux and there is a more heating; moreover in the under excited region, the flux produced by the armature current adds to the flux produced by the field. So, during this under excited zone, here what happens? The flux produced by the armature current that is your even though Fa sorry here Fa but adds to the Ff that is the resultant F.

So, there is a more again flux. So, the heating due to this end field, it is more in the under excited. Therefore, end flux enhances the axial flux in the end region and resulting in a severe heating will severely affect the output of generators.

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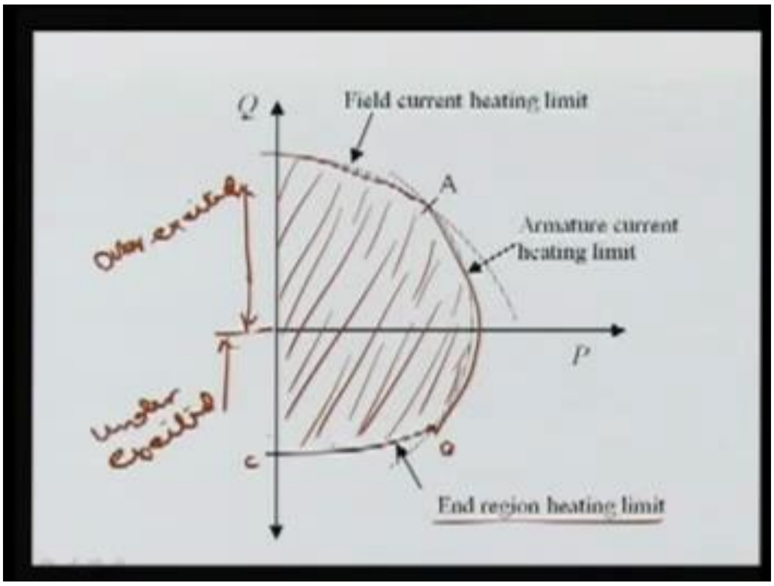

So, if you will see as I said, this is your overexcited area; here is your overexcited and from here, it is your under excited. I said this field end region heating limit is prominent only in this zone. So, now our whole characteristic, since, it is coming here; this is upper. So, always we have to take the minimum value. So, the capability curve here, it will follow up to point A, it is end due to the field current heating limit, and from A here to B, it is due to the armature current heating limit, and from B to here C, I can say end region heating limit. So, this area is basically your capability curve of your alternator; this is a shaded area, it is your operator.

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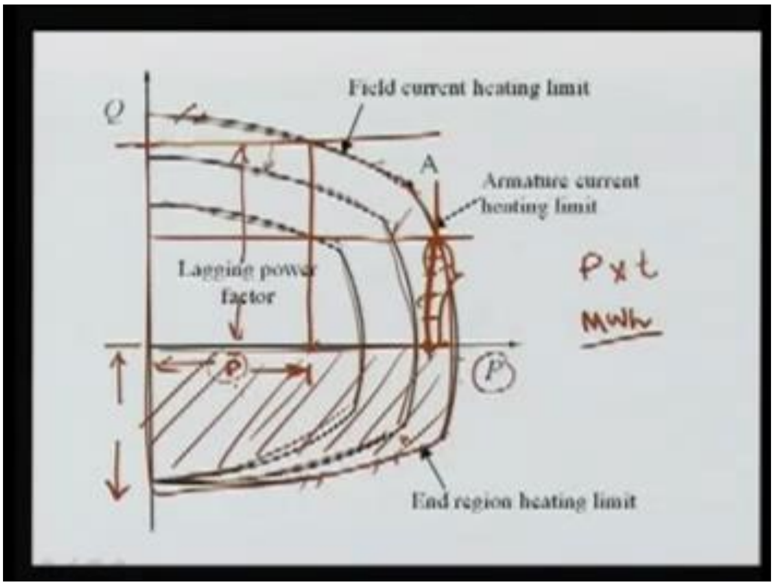

Now let us see basically this was the case when there is an ideal condition means your cooling system is proper. Now in this case if your cooling system is not so effective means your cooling system, for example, if you are having your hydrogen cooling, your hydrogen pressure is reduced, then means your cooling is not so proper, and it is also cooling is reduced. So, your capability curve in the normal condition here, we can go for this curve the outer curve here and this is region of your capability of generator is surrounded by this region or inside the region here means from here and here this is your normal condition.

But if cooling is not proper, cooling is reduced or less due to the various reasons of the system, then your capability curve will be getting reduced and then we have to shift our curve inside this and it will be like this. So, at the various pressure of hydrogen cooling, this curve will be like this. So, you can keep on reducing curve, and your capability curve keep on reducing. So, this is your capability curve of a generator. Now you can see there are certain things means you can generate the reactive power without violating the limit of reactive power; means the main intention of generating stations to generate the real power because they are paid for that.

So, that this real power P is the main criteria, and on basis of that, they get payment; means this P multiplied by time, normally we can see here megawatt, and it is h. This is the energy and for that they are normally paid. So, the reactive power once they are generating, what will happen? For the reacting power of the generators, normally they are not getting paid for that, but in the competitive power market, presently, we are having and then due to this, we are now also going to give the reactive power generation. Now you can see a generator which is generating real power here; let us suppose it is generating here.

So, it can generate the reactive power here up to from here to this value means if this is your real power generation of your generator. So, you can generate reactive power within this limit. So, whether you are generating this or this or this or here up to this point, there is a no loss of real power generation. So, you can generate up to here, and again this is there is no opportunity loss here but you can see. If you want to generate more reactive power, let us suppose you want to generate reactive power here at this point. So, the reactive power if you want to generate this much, what is happening? Your real power will be coming here.

So, this point means your real power, you are now limiting means you cannot generate more than this power for this reactive power. This is your reactive power requirement; what happened? Means you cannot generate more than that is the real power, and if you are going to get money only for this P, you are losing the opportunity in this market. So, the generators, they try to operate, so that they can get the maximum benefit maximum money from the system. So, here they are losing the opportunity to generate the real power, since, they are going to generate here only this power.

So, basically they must be paid for that, and this competitive power market, presently, we will see in the end module, our market scenario is emerging means now each generator is going to compete to other generators. And the market settling and market clearing price will be decided. So, we will see later about this competitive power market or you can say power system restructuring that is happening all over the world, and most of the countries they had gone for the competitive mode. So, the electricity price changes every half an hour or even though one hour.

For in case of England that is UK, the price of every half an hour for whole 24 hours of a day, it is keep on changing; it depends upon how much generating capability are there, how much generators are bid in and of what is again the demand at that time, and this market clearing price are decided. And based on that, the customers are charged and the generators are paid; we will see later in the last module of this. So, this is capability curve; you can see that for more reactive power generator, the generator is unable to generate more real power means he is losing the money.

But at certain point here after we can say up to this reacting power, he can generate this much without losing much real power. So, this is a capability curve, and again it is a heating. One thing I want to mention that is very very important that this zone is normally not allowed that generator should operate. The operating instructions are given to the operator that try not to operate in this zone here, because this zone is very very critical. That creates lot of vibration and the hunting in the synchronous generator. So, this zone is only utilized when there is a black start.

When generator is going to start its power, when there is a blackout; means it is going to synchronize with the transmission system, then we can ask the transmission line generating company to absorb, because the generation of the reactive power through the transmission line is more at that time. Here you will see in this capability curve, this first quadrant.

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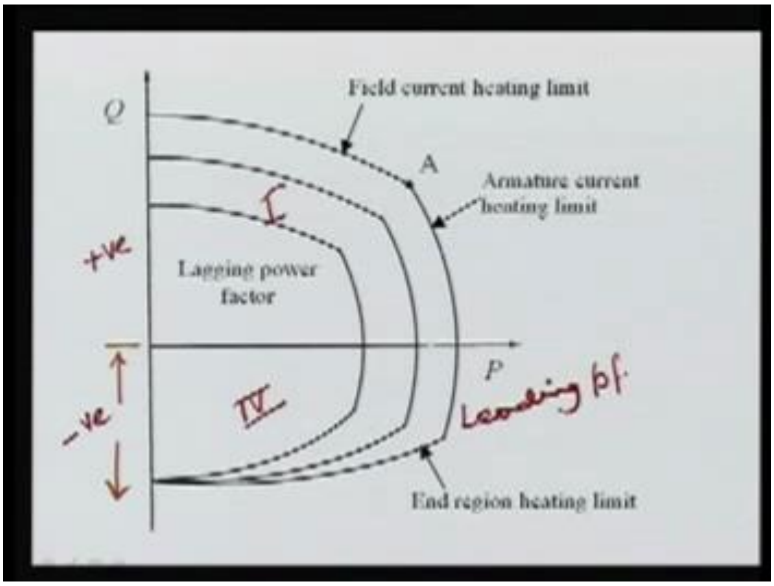

The quadrant number here I can say it is first, it is your forth quadrant normally we call, because here this Q is negative, P is positive; means here the positive Q, here it is your negative Q. And this here the forth quadrant, it is your leading power factor. So, we are normally not allowing with the leading power factor. The reason as I said, operating this zone is very critical in terms of your generation of reactive power you are generating negative reactive power; at that time, the generators normally experience or hunting in this vibration another lot of problem occurs in this.

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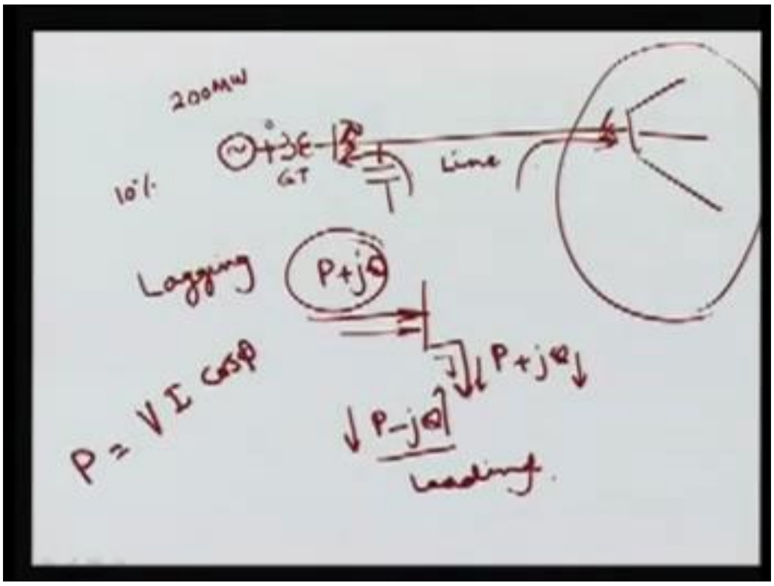

Now you can see a simple generator that is we have and let us suppose we have connecting here with a transformer, and we are having a big transmission line, then we have the several other lines. Now if this is your normally circuit breaker this line means this is your generating let us suppose your 220 megawatt unit and we are having a transformer here means that is a generating transformer GT and this is your transmission line. Now if you want to connect this generator with this whole system that is a big system here that is operating, what happens? Normally we charge this line without loading this line, because initially, this generator is operating at the minimum power; that is normally it is only allowed the 10 % that it will be generating.

And you know it requires the thermal power station, it is required 10 % of its rated capacity. So, its auxiliary requires some power. So, this generator is initially running at the very small load. So, we cannot load, we do not know how much load is required. So, to connect this, this line is normally open and then we are connecting this here circuit breaker; let us suppose this circuit breaker is connected or if your circuit breaker here you can connect this here.

What happens? This is very huge line; loading is less. So, this line is basically you know there are here the capacitances that are distributed in nature, and this capacitance basically generates the reactive power. That reactive power is flowing this side and this side of the system. So, that reactive power generated must be absorbed by this generating station and this plant, and therefore, here this we have to operate in this zone. So, when at the time of light load or during this black start means when you are energizing that synchronous generator, then only we have to operate in this zone.

So, normally, the lagging power factor here in this zone the lagging power factor as I said if this is your Vt, here the power is going means P+jQ if Q is positive, we say the lagging. So, always we operate the lagging power factor of the synchronous generator. However, we do not want the lagging power factor for the load. The reason behind that we want if load is there here, what will be the direction of this P? If you are going here for j plus Q, we say the lagging power factor; here this power is coming out. So, we want that the reactive power should be in the reverse way means we want that the leading power factor that is jQ means P will be coming here from this zone and Q is coming inserted into the power system.

So, the power factor in terms of load, we want the leading power factor or unity power factor. However for the generators, at the normal condition we want the lagging power factor, so that we can provide the reactive power support to this system. So, this is only the difference here, because this is we are injecting power into the system, and it is taking powers from the system. So, the load if you are connecting here, then it must be leading per unity power factor, so that we require less reactive power from the system or if we can store the reactive power, it is better as well.

So, this is related to your capability curve here as I explained. Now let us come on the transformers. We saw the limitations of generator that is a voltage limit, your thermal limits, the three end curves that is reactive power capability and again due to the cooling limits and the turbine limits that limits your complete output of your generator. So, transformer is a device; transformer is very widely used in the power system, because whenever you require the voltage lift or step-up voltage, then we have to use and at the same time, we have to use the step-down voltage, because we know this generation capability, the voltage is limited due to the insulation.

So, we are able to generate at the certain rated voltage, and presently, it is not more than 21 KV in our country. So, if you are transmitting bulk amount of power at the 21 KV, you require huge several lines and also there will be huge loss in the power system. To reduce the loss you know, we had to go for the high voltage because for the same power we know this here. If you are using this P is related with this your V into I cos phi for more power as I said here if you want to increase the power.

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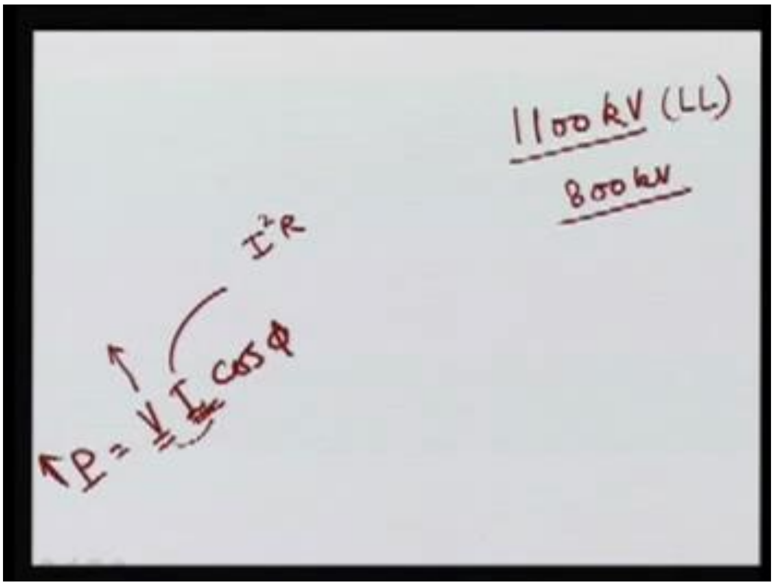

Then if you are increasing the current, there are two options; either you can increase the voltage or you can increase the current or you can increase both. So, increase in the current directly we know this loss that is I^2R loss, it will be very high. So, normally, we try to current constant, and we can increase the voltage of course increase in voltage has also some limitations that is how much that insulation we are going to make. Means for the transmission line if we are going for high voltage, then the requirement of insulator will very very high and also the cross arm are right of way; that is also very high.

So, this is also limited in the transmission line, but anyhow, we had capability that we can go the transmission voltage up to 1100 kilovolt; that is here, it is line to line. However in India, we have this 800 KV system again that is operating at the 400 KV systems. But we have the line which is designed on this insulation level; whenever you want to lift the voltage increase that, you have to change the service station in apparatus and then we can operate again at 800 KV. And again we will see when I will be discussing about the transmission line; we will see the surge impedance loading of this transmission line is very very high four times almost than your 400 KV transmission line.

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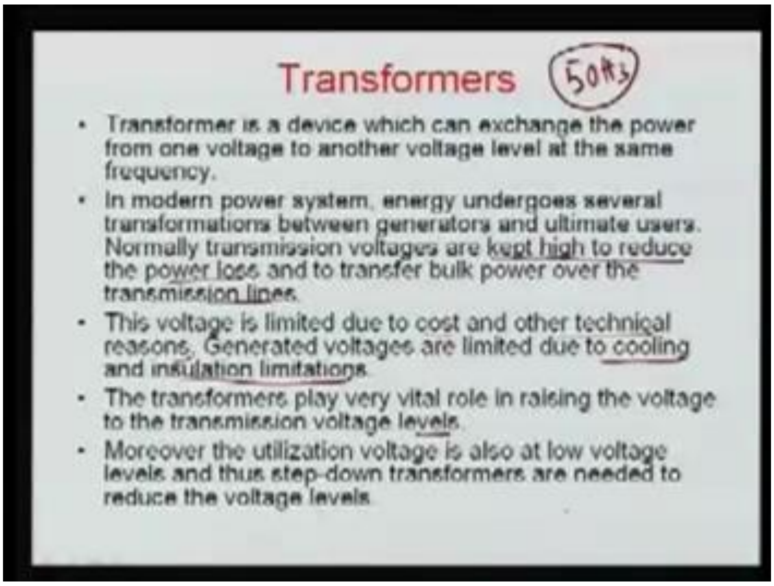

So, transformer as I said here is your device which can exchange power from one voltage to another voltage level at the same frequency. If you are applying the 50 hertz, it will be you 50 hertz output. If you are applying 48 hertz, output will be 48 hertz. Now again sometimes a question is asked if your transformer is rated at the 50 hertz and once we are connecting a supply system with the 25 hertz in the primary, what will be the output and what will be the performance of the system. Output will be the no doubt; it will be according to the voltage of the secondary, it is related with their turn ratio. Primary over secondary is your turn ratio, then your output accordingly it will be changed.

But the output frequency it will be the same 25 hertz, but the performance of this device once it is made and to operate satisfactory and then give the better performance at the 50 hertz; at the 25 hertz supply system, its performance will be not good. Means there will be more losses; its efficiency will be less. There will be other problems heating, etcetera in the transformer. So, normally as in our country, it is your 50 hertz supply system. So, our supply system is only it is a nominal frequency. So, it may be ±3% operation and that is tolerable.

In modern power system, energy undergoes several transformations between the generations that are at the generating stations and the ultimate users that is your customers. Normally transmission voltages are kept high to reduce the power loss; as I said, we have to go for the high voltage to reduce the loss and to transfer bulk power over the transmission line. It is not only loss to go for the higher power as well we have to go for high voltage. This voltage is limited due to cost and the other technical reasons means again you cannot go for very very high voltage; you cannot go for the several millions of kilovolt.

It is only limitation that we can go up to certain level, and the limitation is your insulation is your right of way and again the cost of your transmission towers, wires, and other losses associated with that. This voltage is limited due to the cost, no doubt. generated voltage are limited due to the cooling and the insulation already we discussed and we saw in the previous lectures and as well as in the previous slides. The transformers play a vital role in raising the voltage to the transmission voltage levels. Moreover, the utilization voltage is also at low voltage level and thus step down transformers are needed to reduce the voltage.

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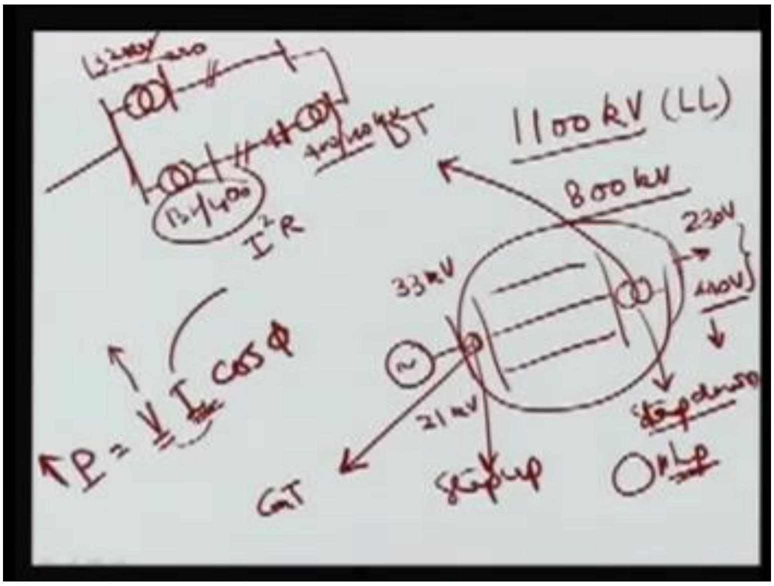

Now you know this transmission always here you are generating at certain voltage; this voltage is limited again as I said. The limited voltage here is 33 KV it is I am talking about the world and it is your 21 KV in India. However, here that is a poor customer is there; why I said poor here because he has to pay all the wears; he has to bear all the cost associated with the generating cost of this power, the transmission cost, etcetera that must be required from the customer. So, this customer also again you know the mostly the customers uses the 230 volts single phase or it may be 440 volt three phase.

Some large customers, they also utilize power at the 11 KV even though some customers utilize at 25 KV; railway utilize 25 KV and also some customers like the fertilizer corporation of India, they use the power at 132 KV they have taken and then they utilize at the various levels. So, we know that we are utilizing power at the low voltage. Now question why not high voltage? You know if you are going for high voltage, then you have to go for the insulation, safety and as well as the cost. If you are going to use a motor, let us suppose a simple that will pump if you are using here one hp motor and this motor at high voltage, then we have to use very high insulation as well and then the cost of here is simple one hp motor that will be several several thousands; it may be in lacs also.

So, end use is always limited to certain voltage and that voltage is no doubt; it is the 440 volt for the domestic purpose, and for the industrial and the other commercial purpose, the voltage may be 11 kV or it may be even though 33 or 25 KV as well. So, now this gap area is the possibility of raising the voltage. So, we can go for the higher voltage transmission lines here and then we require here the transformers and also we require the transformer that will reduce the voltage. So, this voltage is your step up voltage transformer, and here it is your step down transformer. Means here the voltage of your secondary side, here this side it is reduced from this side.

So, we are using the transformers is step up and the step down transformer. So, we are using both types of transformers. Normally, the transformer near to the generating station they are step up and other transformer near to the end user they are step down transformer. However, we also use some other transformer. So, the transformer which you near to the generating station, it is called the GT generating station transformer. If you are using at the distribution level, then it is called DT and the distribution transformer.

The transformer in intermediate this transmission lines; for example, if you are having here 132 KV bus, then you want to lift this voltage to 220 volt and then we are having this line. There is a possibility here we are having another transmission line and then we are lifting here into 400 KV line, then we are having another transformer and then we are connecting with the system here. So, what happens? This is your maybe 132 / 400 KV; this is your 132 / 220, and again here we are having 400 / 220 KV transformers. So, these transformers are called power transformers, and they are using the transmission system for connecting the different level of voltages.

So, you can see here 132 bus here the different lines; they are connected with the 220; they are connected with the 400. Again we are using the different rating and different voltage level of the transformer.

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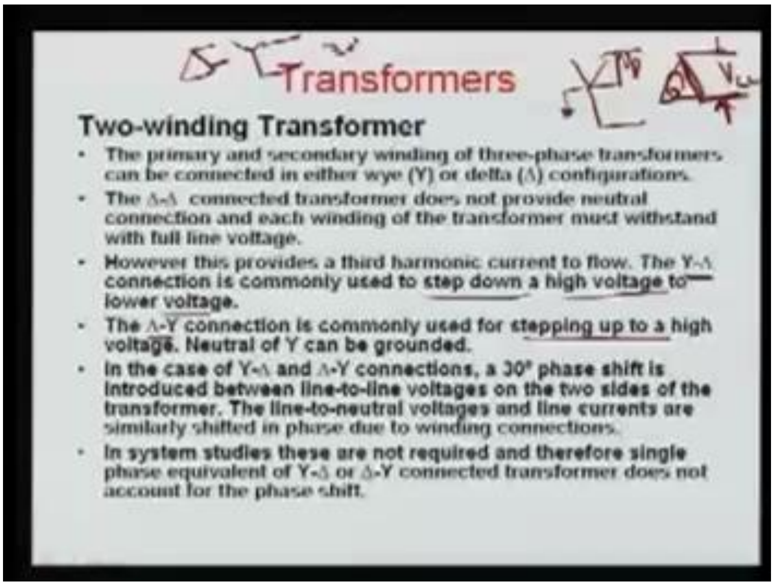

Now we will see the different type of transformers those are used in the power system. First one is the two winding transformer that is very common; for the three phase applications, the primary and secondary winding of the three phase transformers can be connected either in y or in delta connection. Means we can have here delta now a star or we can have here the delta; this is also called y or a star and this is called the delta if you are connecting like this. Delta-delta connected transformers does not provide the neutral connection; here you can say you can connect here the neutral, and the neutral is required sometimes to have the proper protection of the system to have several advantage of this neutral connection, but here there is no neutral there.

So, each winding of the transformer must withstand or with full line voltage. You can see here the phases here; they are bearing the line to line voltage. This is your V LL that is you line to line voltage. Here the phase is only this line voltage and this is another line. So, it is only this phase voltage bearing. So, insulation level of the phases is also reduced here in the star connection; however, this provides up third harmonic current flow. What happens in the delta? If there will be any third harmonics we know in power systems, there are the various types of harmonics.

And the third harmonics sometimes also called the triple-n harmonics. What happens? They will not flow, and they will keep on rotating in the winding. So, they are not going into the system; they are here just circulating here in the winding, and that energy is basically dissipated in terms of loss, and finally, it is cooled down. So, they are not going into the system; this is one of the beauty of the delta winding transformer. The delta star connection is commonly used to step down a high voltage to lower voltage. Means we use star delta connection for the step down transformer, and this delta star is normally used for the stepping out high voltage where the neutral can be grounded; neutral we can ground it.

In the case of star delta or delta star connections of 30 degrees phase shift is introduced between line to line voltages on the both sides. If here means if you are using here star and the delta, the line to line voltage here and the line to line voltage, there will be 30 degree phase. And again it depends upon star to delta and delta to star that there will be 30 degrees shift from the both side. So, line to neutral voltages and the line currents are similarly shifted in the phase due to the winding connections. In system studies, these are not required, and therefore, single phase equivalent of star delta or delta star connected transformer does not account for the shift.

In the study, we do not go for the shifting. So, they are not considered at all and then we can go for the single phase equivalent of these transformers and without any loss of generality. We also use sometimes three winding transformers, and it is called primary, secondary and third one is called tertiary winding.

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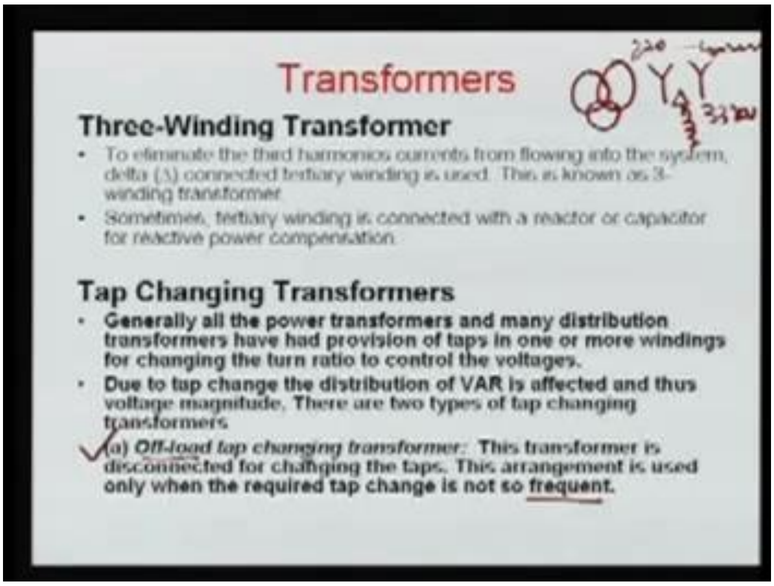

To eliminate the third harmonics current from the flowing into the system, a delta connected tertiary winding is used; this is known as the three winding transformer. Normally, its representation here we can say this is primary; this is your secondary and we go for another tertiary. So, here if it is a star-star two winding transformer and then here the third tertiary will be the delta; this delta basically use that the third harmonic should not intend in to the system, and it must be rotating here in the delta connected, and it is dissipated. So, this is advantage. Sometimes, this winding is also used to connect a reactor or sometimes from here we can use some reactor, because this voltage is very very low.

If you are using here let us suppose 220 and here 400 KV, then this voltage may be your 33KV and then you can connect some reactor; you can connect some capacitor. Normally in this we normally use in the power transmission line, we use the reactor because when the loading is less, at that time we require reactor to put into the service to reduce the voltage of the system. Because at that time, the transmission lines they generate more reactive power, and that here reactors they absorb it. Another here transformers category, the transformer may have the tap changing facility; it may not have the tap changing facility.

Generally all power transformer and the mainly distribution transformers have had provision of taps in one or more winding for changing the turn ratio to control the voltage. Due to the tap changing, the distribution of reacting power that is VAR is affected and thus voltage magnitude, because if we are changing the reactive power flow, reactive power in this injection or absorption, there will be change in the voltage. There are two types of tap changing facility those are available. First one is called here offload tap changing transformer. Here off load itself indicates that you cannot change the tap during the energize condition.

For changing the tap, you have to de-energize this transformer means you have to take it our from the service, then you have to change the taps and then you can put into service. It does not means that de-energization means you have to take the transformer somewhere else and you have to change. Means you have to isolate this transformer from the system and then you can change the tapping and then again you can reconnect. So, this arrangement is used only when required tap change is not so frequent; means if you require suppose monthly or even though seasonally, then normally this specialty is provided in those transformers.

Because you know in some seasons, the load is more, voltage is less, then you may require the different type of changing position in different when the off peak load, there will be more voltage then you may go for less tapping, so on and so forth; means it is not so frequent, then we can use offload tap changing transformers.

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Another type is that is, of course, that was off load. Now it is called on load tap changing and it is also called OLTC transformer. It is used when tap changing requirement is frequent, and it is not possible to de-energize in the line especially in the power line having bulk power transmission lines those are connected with the lower voltage and higher voltage, the transformer is used. And that transformer is not possible to take it out means it is not possible to de-energize and then change the tap. So, in those cases, we use the online tap changing facility that is built in and there is a voltage sensing mechanics circuitry that automatically senses the voltage.

And based on that, it changes the taps to maintain the voltage of that bus. Where ever you are sensing the voltage, it is tried to maintain that voltage at its regulated at its control value. The step down transformer usually has the OLTC in the low voltage winding and de-energized tap in the high voltage tap. We require this OLTC in the low voltage because we are going in the low voltage that again always we have to see if your transformer here, there are tapped. What is the potential difference between two taps? If it is very high if we are changing from here, there may be some spark, etcetera. So, we try to have the minimum voltage step here, so that we are going for the low voltage side.

Another type of transformer that is used in the power system, they are called basically the boosting transformers or regulating transformers. To control the voltage magnitude and phase angle or even though phase angle, regulating transformers are used which add a small component of voltage normally less than one per unit to the line or phase voltages. These transformers are having several advantages over the previous transformer. There is no need of tapping in the main transformer; here if you are having this regulating transformer or booster transformers, there is no need of going for the tapping’s in those transformers.

These transformers can be used at any intermediate point in the system means you can use anywhere in the transmission line anywhere to control the voltage or to provide the phase shift. These transformers can be taken out of service for the maintenance without much affecting the system, because they are in a system and their purpose is to control the voltage or phase angle. They can be taken out without any problem and then we can monitor, we can maintenance, we can do some sought of analysis or even though we can do some maintenance work and then we can put in the system without any problem.

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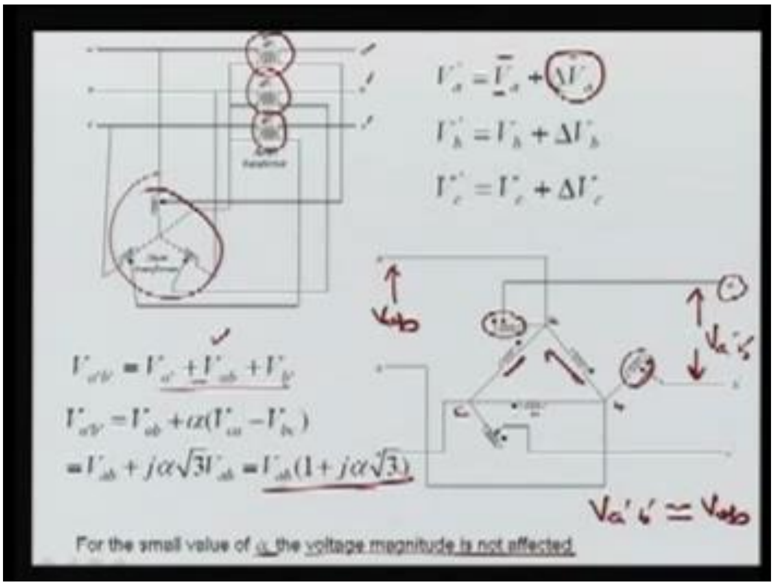

So, you can say the boosting transformer may be of two types. Here this is a transformer; you can say this is a shunt transformer here we have added, and this voltage is basically coming here, and they are adding the phase voltage here in the A phase, here it in the B phase, and this is in your C phase. So, the voltage here A prime B prime and C prime means A prime will be the voltage here that is Va plus the change in the voltage which we are achieving from phase A. So, we are just lifting, we are just injecting the voltage and that is in the same phase.

So, what is happening? We are increasing the voltage. So, without here changing the shift, here we are increasing the voltage here and that is in the series of this circuit. Means we are taking here some voltage the phase voltage and we are injecting this voltage and this is called your here the voltage control or boosting transformer. Another type of here that is called the phase shifting transformer, you can say this is a transformer; this is A phase, B phase and C phase. We have here delta connected.

Now you can see in this delta connected this A prime can be written, the voltage between these A prime and here; that is called $V_{a'b'}$will be your the voltage $V_a + V_{ab}$. Here this is your V; this is your ab. So, this voltage addition means you are adding this voltage $V_a - V_b$ this voltage, then we are adding $V_{a'}$ and then we are adding $V_{b'}$. What is the $V_{b'}$? This is your $V_{b'}$; this is your $V_{a'}$, and we are adding together here. So, we are getting the V_{ab}.

Now you can see we can simplify and we can write this $V_{a'b'}$ will be equal to your Vab; that is the line to line voltage here this side. This voltage is your Vab plus here this two basically the difference of Vca; what is this voltage $V_{a'}$? This voltage prime is related here this is c. So, this voltage is going to be induced here and the some fraction of you can say the factor α that is Vca and your Vbc. This is Vbc, and this is your this voltage is related with this voltage Vca. So, these are going to be added and then we can see here this is under root three times.

And finally, we can write the $V_{a'b'}$ will be equal to your $V_{ab}\,(1 + j\alpha\sqrt{3})$. Now for a small value of α, the voltage magnitude is not affected, and however, we are providing the phase shift. Here if this is very small, this voltage magnitude will be equal to your Vab means Va prime b prime is approximately Vab, but we are getting some phase shift here, and that is basically your phase shifting transformer.

So, these phase shifting transformers were earlier stage they were used, but nowadays, they are not used, because we are going for the solid state phase shifting device that is called thyristor controlled phase shifter; they are very very good compared to this transformers. We will see again in the module number three, there are some facts and HVDS devices, then we will see some TCBR, etcetera.

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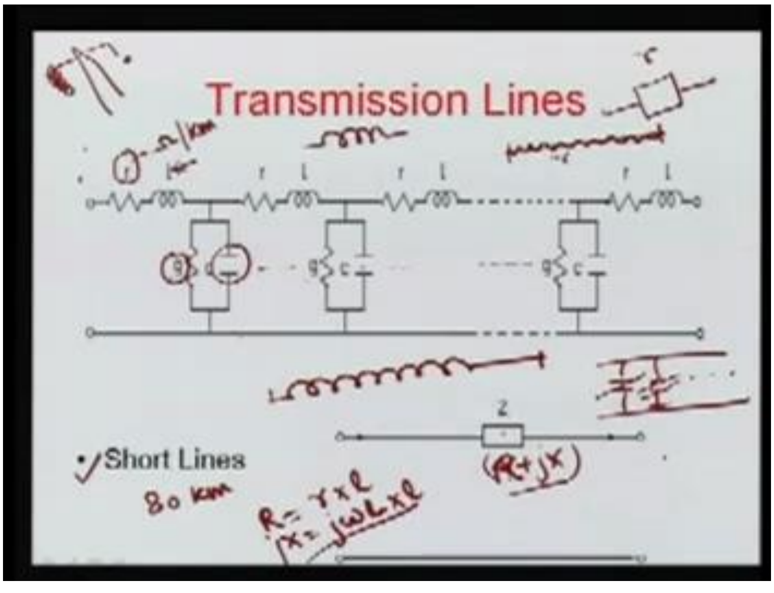

Now let us go for the transmission lines. The transmission lines what is the capability, what are their characteristics; we will see here in the transmission line module. In the previous slides, we saw the transformer capability. The transformers are rated to its rated voltage; again the voltage is limited by the insulations of the windings. How much winding, what is the level of insulation we are going to have, and also what type of cooling you are going to have? Power rating is decided by the cooling of the system means your cooling is very strong very good, then you can go for more loading and so on, so forth.

So, this limitation of the transformer is basically related with the voltage limit; again that voltage is due to your heating limit and insulation limit as well. And your cooling systems provide that how much power we can load means how much current we can go for. And that basically how much radius what means the diameter of the winding, so that we can flow the current without excessively loosing the loss. So, let us see the transmission lines as I said the transmission line is a backbone of any power system, and we have the several transmission lines of different voltages. And they are connected with no doubt that various transformers and here the transmission line is basically carrier of electron, or you can say in other words, they are carrying power from generating stations.

And finally, they are delivering power to your end users or you can say customers. The transmission lines you know we have the wire, it is in kilometers long. So, we are having the resistances means the wire will have some resistance r and this r will ofcourse it will be your distributed means r per ohm. So, the unit r here is ohm per kilometer r per meter. So, r is uniformly distributed; it is not lumped. For example, lump means here if you are using a resistor here, this is your r. So, it is called lumped parameter, but here if this r is the throughout here, this is your length.

So, r here is distributed here means we are having here r like this. Similarly, if you see other parameters of transmission lines, they are here the inductor l, and they are also distributed in nature. We have the capacitance due to the different here from phase to neutral because there is a different voltage. We know this inductor is due to the current which is flowing in the conductor and the flux is introduced that is a magnetic flux. Here the capacitor due to the charge on the conductor and here neutral potential, there is a potential difference and then we form the capacitance.

So, we had this l that is an inductor. We have the capacitance of the form and they are here you can say the distributed means every here smaller section we can write here the inductors are now distributed throughout the length of the line. Similarly, we have the capacitances here, capacitances here, and they are distributed in the nature. Another term that is called g r conductance, they are also there. They are nothing but some losses, and those losses basically occurs at the level of insulators means because this transmission line; here the transmission line is supported by a tower and here we are having supported.

And there are some insulators those are insulating the power conductor from the arc potential. So, there will be here some leakage current over the insulator, and that loss is normally denoted by g and since we are having the towers at the equal distance and throughout the transmission line. So, this g term that is a conductance that is loss due to the several other factors, it is also distributed in nature. Now to analyze, it is very difficult that we can go for all the distributed parameters. So, normally the lines are categorized into the three categories.

First one is your short lines. The short lines are the lines which are less than 80 kilometers or you can say 60 miles. Then in that case, what we normally assume this capacitance is ignored means there is a charging is very very small. So, we can simply the transmission line can be represented as here the lump parameter that is your r+jx and here we can here make the study with simple the lumped parameter of the resistance. Here your r is nothing but now you can write here capital R and here capital X.

It is your r into the length of line, and here x is nothing but your j omega basically already I have written j here j x omega l that is here l into length of the line, $(R+Jx) = (rl+j\omega xl)$. So, here we have assumed that lumped parameter and then we can make analysis by ignoring the charging or you can say some capacitances. So, this is your short lines.

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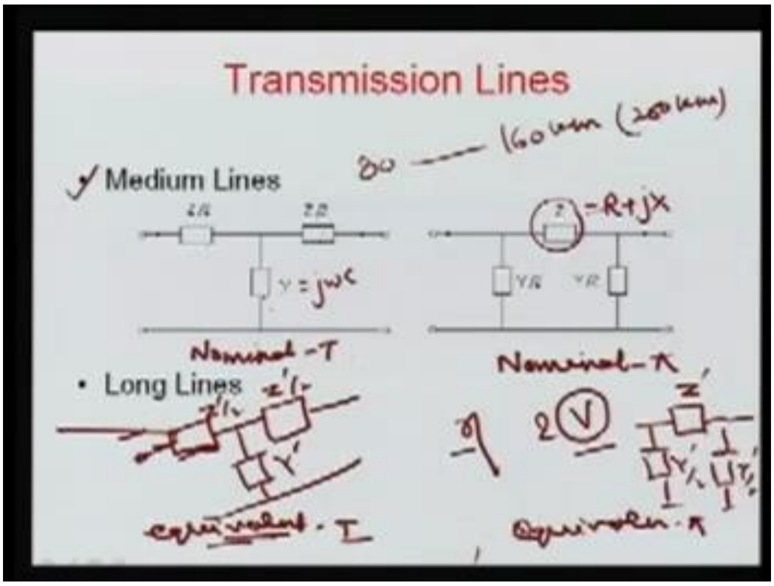

Another is your medium line; medium line is the line which is more than 80kilometers to it is less than 160 kilometers or in some cases, it is taken up to 200 kilometers. Then it is your medium line and for medium line, we cannot ignore; we cannot ignore the charging. So, we had to take the charging but only in the medium line, the distributed parameter can be considered as a lumped parameter. So, this distributed parameter because there we are having series and shunt component, where this shunt parameter will be connected that decide which type of configuration we are using.

If all this charging, the capacitances are lumped here in the y that is your j omega c; it is completely that is lumped parameter if you are using in the middle of the line. And here your impedances that are lumped are divided into two half of this, then it is called your nominal T representation of the medium line, and then we can analyze the line with this representation as well. We can also use this now the series part; this is series impedance; this is shunt admittance. So, series impedance if it is lumped together, here it is nothing but your R + j X.

It is one, then we can separate out this charging part into two halves of both side, and this is called your nominal pi. You can say this is just like a pi, and then we can analyze the performance of the transmission line. And the performance is nothing but your efficiency and your voltage regulation of the transmission line. So, the voltage regulation also limits; you know if a line is loaded and the line is thrown off means load is thrown off, then what will be the voltage raise in your receiving end? So, why the efficiency and what will be the voltage regulation; basically, these are the two performances. These are the two parameters of the transmission line performance and that basically we analyze.

In long transmission line, basically, it is not possible means we cannot assume that these parameters are lumped. Means we have to consider the distributed parameters; we have to consider the distributed equivalent. And that case, it is called equivalent T or equivalent pi means here we have to go for this is your similar like here T and this is your y. Here it is I cannot write here this is omega c; it is a different parameter, and it is in terms of hyperbolic functions. So, this is y prime, here z prime by 2, here z prime by 2.

So, here what we do? We normally go for exact formulation of the transmission line in terms of distributed parameters, then we can go for analysis, we can form; we can calculate this z primes and y primes in this representation. So, it is called equivalent. Here it is nominal, because we have taken assumption that your parameters are lumped; the distributed parameters are considered as the lumped parameters. Here it is an equivalent because we are analyzing the line as an actual. There is no assumption and then we are representing in terms of T; that is why it is called equivalent T.

Similarly, here in the equivalent pi, we can represent this pi circuit like this; this is your pi as previous case. Here this is your again z prime, here y prime by 2, here y prime by 2. So, here this again z prime and y primes are calculated, and it is basically based on the equivalent or exact analysis of the transmission line. Now I am not going to calculate because already I think you have studied this in the elements of power system where the calculation, etcetera is known to you. Now let us see the capability and the limits of the transmission lines.

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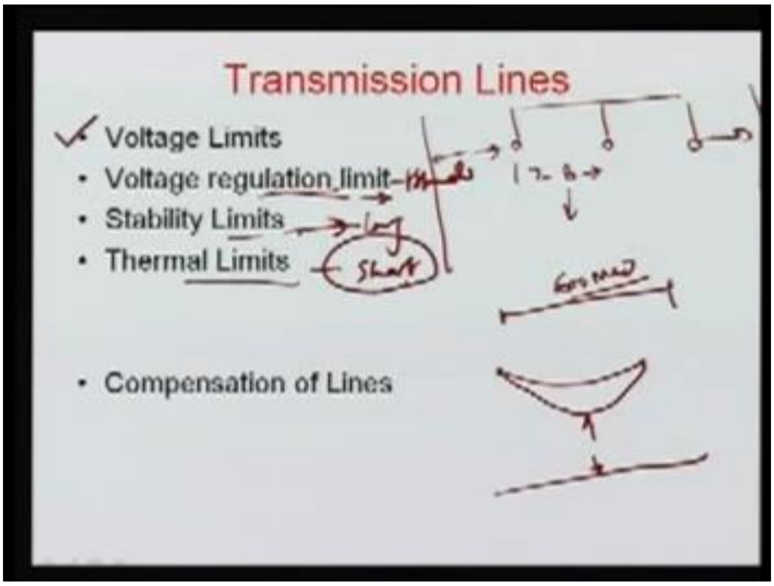

Here the various limit is I can say first one and that is very important is the voltage limit. As I mentioned it from very beginning, then we have the voltage; in India, the maximum insulation voltage of the transmission line that is of 800 KV, although, it is operating at the 400 KV. So, the voltage we cannot keep on increasing high; the reason behind that we should have the more right of way. Right of way means here the spacing between the three conductors here; it is normally 7 to 8 meters for even the lower voltage and sometimes it goes up to the 15 meters.

So, what happens if you going for more and more voltage? This spacing will be more and more increasing, and finally, it will be very uneconomical means we have to go for very huge towers and the cost will be very very high. At the same time if this is your tower which is here, it is at some tower it is running, then we require some right of way; means we require here this conductor from this side also there should not be any tree; here also this end there will not be any tree. So, we require very huge margin; it may be sometimes 40 meter.

So, you require complete right of way and again if you are going more and more of voltage, then you require more and more right of way problem; means you have to have their should not be any trees; there should not be any house and so on, so forth. At the same time if you are going for higher voltage, some other losses are very very prominent.

For example, if you are going for higher voltage, then there will be more corona loss, and also you require more insulators and then again upward, the cost will be more.

Another limit is your voltage regulation limit. The voltage regulation limit basically it is very prominent especially in your medium transmission line. If you are designing medium transmission line, the voltage regulation is the major concern how much drop you are going to achieve and that is here it is far for your medium transmission line. The stability limit is very prominent if the transmission line is very long. As you know the transmission line if it is very long, then it is not possible to transfer more power than its surge impedance loading.

So, another is your thermal limit. Thermal limit is the limit if you are exceeding that power that is more than its limit; there will be some sag. Means your transmission line is this; there will be means not like a completely straight line. Here there is a two towers; here your normally sag is like this your transmission line. If you are going for more loading, what we will have? There will more sag and they would have ground here. So, your clearance here is reduced, and there may be possibility of the danger of life. At the same time, there will be possibility of the flash over here. So, we cannot go for more loading due to the thermal limit.

Normally, this is more prominent in case of the short transmission line; in the short transmission line, the stability concern is not the major concern. Normally, the thermal limit is the governing criteria; however, in the long transmission line, the stability limit is the governing criteria, because we cannot load more loading than the thermal limit. So, the stability limit is always less than your thermal limit. So, we have to consider the thermal limit for the short transmission line.

If your transmission line surge impedance loading of this line let us suppose 600 megawatt, this line can be loaded up to even though 800 megawatt without violating this; it is we can go up to the thermal limit, but if transmission line is very long, then even though we cannot load more than its stability limit which is much much lesser than the thermal limit. So, this will be the governing criteria for it is for long line; this is for your medium line, and this is for your short line.

So, if you are having the long transmission line, what you can do? We have to transfer the power; we know nowadays your generating stations at they are not at this load centers. They are very far from the load centers, then we are having very large transmission line and then we have to compensate; we have to improve the stability of the line, so that we can load more and then we have to go for compensating the transmission lines. And this compensation I will discuss in this next lecture.

Thank you.