Power System Operations and Control
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Module - 02
Lecture - 02

Now welcome to lecture number two of module two that is equipment and stability constraints in the power system. In lecture one, we saw that per unit system and also the various constraints related to the equipments and the system. Here now we are going to discuss the various equipments those are very important in the power system and the first one is your generation.

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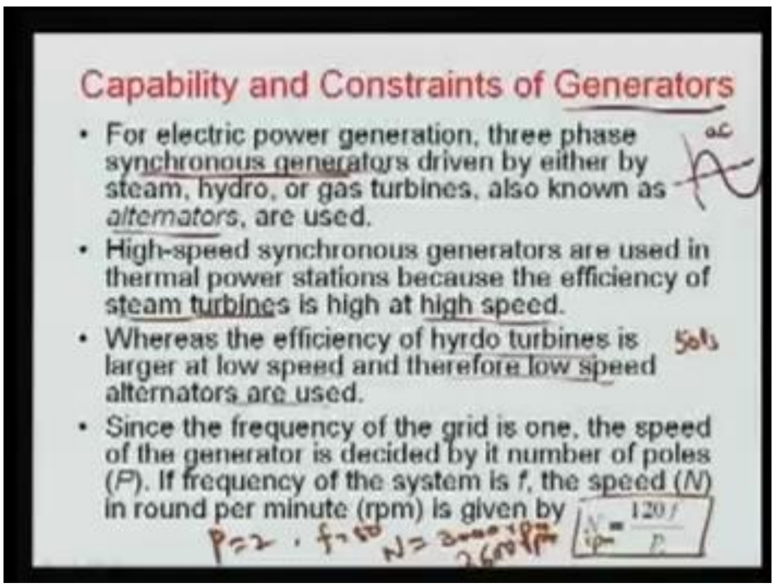

Already, we know this power system that we have the synchronous alternators, and as I said, the alternators because they produce the alternating currents or you can say sometimes very conveniently reset the AC currents are used, and these alternators are basically run by the turbines. And the turbine is basically rotated with the different mechanism, whether it is due to the stream or through the hydro or through the gas, and then based on that, we say the stream turbine, hydro turbine or your gas turbine.

There is a different type of synchronous alternators; one is your cylindrical, another is your salient type. In the cylindrical, it is normally number of poles are limited; however, in the salient, the poles are more, and the poles are at the salient in nature. High speed synchronous generators are used in thermal power stations or you can say stream turbines, where the stream turbines are used; we go for the high speed alternators, because the efficiency of the stream turbine is high at the high speed. Whereas it is reverse in the hydro, hydro turbines; the performance is better at the lowest speed.

So, the stream turbine that is here gives the better performances in terms of efficiency and in terms of operation and then we run at the highest speed. Whereas the efficiency of hydro turbines is larger at the lowest speed, and therefore, lower speed alternators are used. Now, how much high you know this we have the 50 hertz supply system and the number of poles in any power system; any alternator cannot be this odd number. It should be even number means the number of poles will be 2, 4, 6, 8 and so on, so forth.

And then, this speed is related by the system frequency and the number of poles, and it will be used and can be given with the equation N; that is the speed in rpm will be equal to 120 multiplied by the system frequency divided by number of poles. So, that is the number of pole in the minimum number of pole cannot be less than here two, and if your system is operating at the 50 hertz, then your N will be your 3000 rpm. However, in the USA, Canada, and Mexico, which is operating at the 60 hertz system, then this will be your 3600 rpm.

So, the maximum speed that we can achieve in any alternators is your 3000 for the 50 hertz cycle system, and it is 3600 for the 60 hertz cycle system. Since, in India, it is 50 hertz supply even though it is not India, it is Asian country as well as the European country; the system supply frequency is 50 hertz. So, the maximum speed of any alternator will be your 3000 rpm, and it is related with this equation that the speed in rpm, it will be 120 f divided by p. P is the number of poles; f is the frequency and 120 is the constant that is multiplied.

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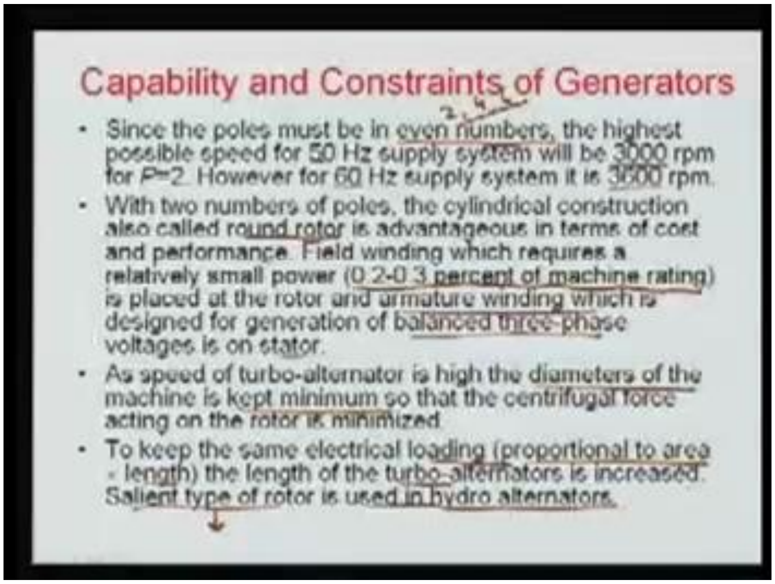

So, that is why here as I said this thermal or you can say stream turbines are more efficient. So, they should have higher efficiency, and for higher efficiency, we have to go for the higher speed. So, if it is the higher speed, then we have to construct our alternator in such a way that it should not be feel high centrifugal force. Otherwise, what will happen? There will be possibility that the poles which on the rotor, it may go out, and that may damage your alternator. So, as I said, the poles cannot be odd number; it will be always even number means the number of poles it will be 2, 4, 6 means it is a factor of 2.

The highest speed as I said it is 3000 for the 50 hertz cycle system, and for the 60 hertz, it is 3600 rpm; with two number of poles the cylindrical construction are also called as a wound rotor, or sometimes called round rotor. It is advantageous in terms of cost and the performance filed winding, which requires a relatively small power. It is normally 0.2 to 3 percent of the machine rating is placed at the rotor, and the armature winding which is designed for generation of balanced three phase voltage is on the stator means the rotor where we put the field.

Now you can assume that you have seen the DC machines. Normally field is in on the stator and the rotor, we have the rotor winding, but here it is different. Means your rotor is on your field winding is or sometimes it is called field winding. It is on your rotor where the armature is on your stator winding. As the speed of turbo-alternator is high, the diameter of machine is kept minimum as I said, why? Because we want that the minimum centrifugal force should be applied, and therefore, we can have the stable machine operation. To keep the same electrical loading, loading you know the proportional of area multiplied by length; the length of turbo alternators is increased.

And whereas salient type of rotor which is used in hydro, the length is minimum, but diameter is more; so, you will find that in thermal power stations, the length of machine is very very large, but the diameter is less. However, it is reverse; in the hydro, it is the diameter is very high whereas the length is less, because here the electrical loading is proportional to the area as length. So, to make the electrical loading same, if you want to go for the minimum dia means area is less, length must be increased. So, in the turbo alternator, the length is very high and diameter is kept as minimum as possible; however, in this hydro, normally we use the salient, because we go for the large number of poles and also they operate at the less speed. So, it is convenient to use the salient type.

And therefore, for the salient type, we can have the large number of poles on the rotors, so that the diameter of this machine is increased. So, of same electrical loading if diameter is increased, we can have a smaller length of this. Also this thermal power alternators, normally it is horizontal, it is rotating. However, in the salient and that is used in the hydro power station; it is vertically, water is coming and that turbine is rotating, and your alternator is connected with this turbine.

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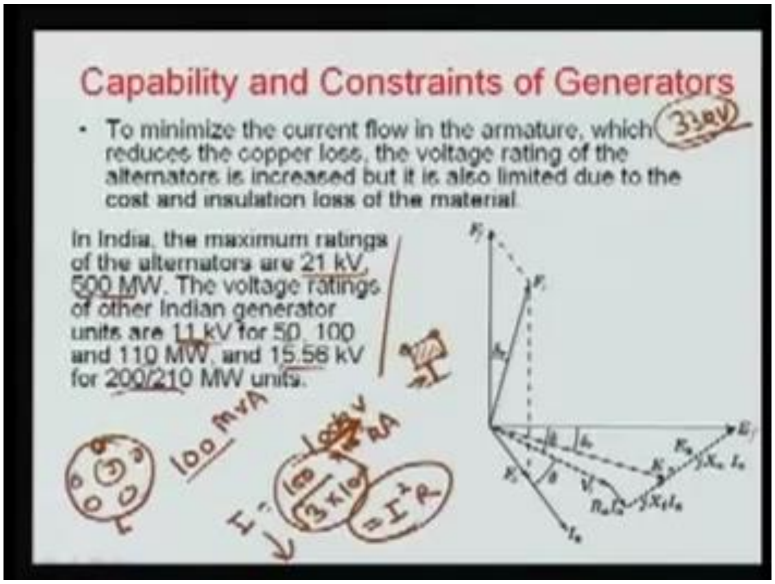

To minimize the current flow in the armature which reduces the copper loss, the voltage rating of the alternator is increased, but it is also limited due to the cost and the insulation loss of the material. As I said if you want to go for higher power and suppose you can see you have a machine that is your 100 MVA. And your voltage is let us suppose 10 KV, then current will be if we are talking here is a three phase. So, then phase current will be 100 divided by under root 310 KV, here it is MVA. So, it will be 10 power 3 Ampere or I can cut out. So, it is kilo ampere.

So, you can see this much kilo ampere current is flowing now. If you want to increase this voltage to 100 KV, what happen? This current is reduced, and once current is reduced, we know this i square R loss that is loss, the real power loss and this loss basically generates heats in the winding. So, what we normally go for? We try to increase the voltage to reduce the losses in the system, but there are two problems with the increase in the voltage. If you are going for the increasing voltage, you know any alternator here this is your armature where the different bindings are here at the stator. And we have rotor that is rotating.

So, this winding is operating at 100 KV and this outside cell, it is ground potential, then we have to go for the insulation level to provide for this higher voltage. Then we have to use the insulating material that can sustain this high voltage level. So, to design it, it is very very expensive to go for this, such a high insulation material. So, what it is limited, we cannot go for keep on increasing the generating voltage. So, that is why we have a limitation here that is the constant of this generating equipment that is a generator; that we cannot increase the voltage as much as possible means we can go up to the certain level, where we can see that we have our dielectric material that can sustain that voltage.
So that there should not be any short circuit; there should not be any fault. That is what is happening if this is your winding conductor and this is your zero potential where your conductor is there. If the insulating material here that is the short circuited, this is just like a line to ground fault. So, this is the fault and that must be protected. And so that we have to put insulating material here in such a way that it can sustain that voltage level. So, the maximum voltage level that is available in the volt, it is not more than 33 KV. Main problem here that we cannot increase the voltage excessively than more than this, because at this counter at the corner here you can see, there will be more field.

The stress the dielectric here this E field will be higher at the corner. If there is any soft corner, there will be more. So, there will be possibility of hot spot and also eddy current and more losses here and there will be some problem here. So, we so far throughout the world, we have the generators rated the voltage rating is up to 33 kV. However, in India, the maximum voltage rating of alternators is 21 KV, and these alternators are rated at the 500 megawatt. We have the alternators at the Singrauli, Rihand and Pared, and they are basically at the 500 megawatt units. It is not a unit means at any power plant station, there may be possibility that we have the several units, and so it is one unit is rated at the 500 megawatt.

The voltage rating of other Indian generator units is 11 KV for the 50, 110, 100 and 15.65 KV; sometimes, it is also called 16 KV for the 200 and 210 megawatt unit. So, we have the two types of alternators; one is your wound rotor, and other is your salient pole. For salient pole, as I said we use these types of alternators in hydro, but for the thermal or you can stream turbines, where they are rotating the alternators, we use wound rotor. Now the phasor diagram to know this other capability, so just these are the various voltages ratings; so, we have seen that the constants of the generating stations or generating units are limited by the voltage due to the dielectric or you can say insulation limit of that.

So, we will see other constraints of and we can say that is a capability of the generators. So, if we will see the capability and the constraints, what is the difference between the capability and the constraints of generators? Basically, there are various constraints those limits the capability of the generator. So, the capability is a curve that is bounded by the regions of the various constraints. So, we will see the capability curve of generators in terms of real and reactive power later, and again that is depends upon the heating limits. We have seen another constraint, and you can say limiting value of the alternator is the voltage due to the dielectric and due to the design limits.

So, the various limits are imposed on any elements; it may be a thermal limit as you can say heating limit, and another one is your electric due to the electric constraints. Now these alternators basically, it is called the double excited means we have the field winding and we give the DC field to this rotor, and we have the armature where the AC is going to be produced. So, we have the field mmf and another we have your armature mmf means we have the mmf at the rotors.

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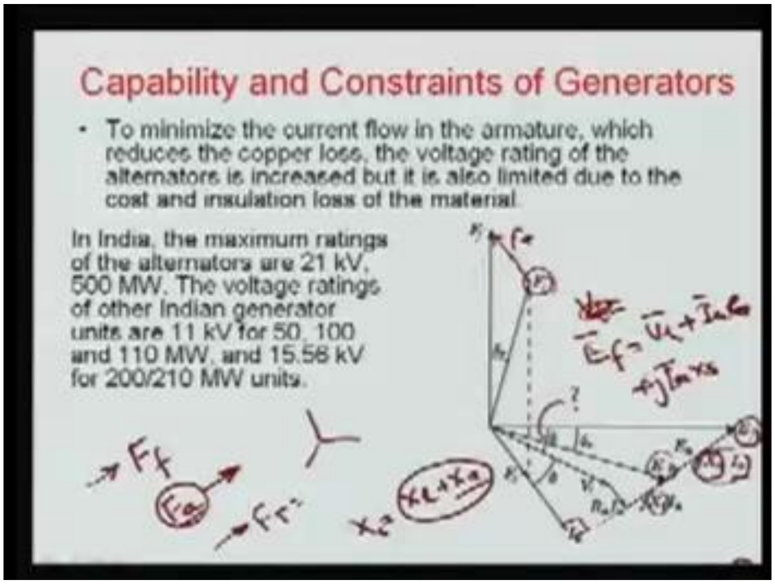

That is called F f and we have F that is of the armature. The resultant if we will see that here we have the armature currents and this resultant of this armature because we have three phase windings, and they are displaced by 120 degree in space, so that you can see the resultant here F t will be also rotating in the air gap; it is flux that mmf will be rotating at the same speed of the operating frequency that is omega 2 pi f. So, then we can have this f is rotating at the synchronous speed. This Ft is also rotating, and this is due to your F a it is rotating with the same speed, then we can add these two mmf.

Here you can see this value F f minus F a; basically, this is called your armature reaction it tries to oppose. So, your resultant mmf will be F r that will be F f minus here F a. Here you can say this F a is added here. So, this resultant will produce your resultant voltage. Now you can see that is this F will give you voltage induce that is E f and this we know it very well. This induces emf E that is produced by the field and we have V r; so, these two are related by another here that is your x a multiplied by I a. And this here is you can say current, it is perpendicular to here means it is at 90 degree. So, what is happening? That is this we have a reactance here x a, and we have the reactance that is leakage reactance of this winding in the generator.

So, we can write the expression and this equivalent if you can say this x that is called synchronous reactance is your addition of x l plus your x a, and this x a is due to the armature reaction. So, this total x is basically the reactance that is seen by generators that is experienced by generators. So, now you can say we can write the equation here your terminal voltage of the generator will be, or in other words, we can write here your E f will be your V t plus your I a r a plus here j I a into x s, and here all these are the phasor quantities.

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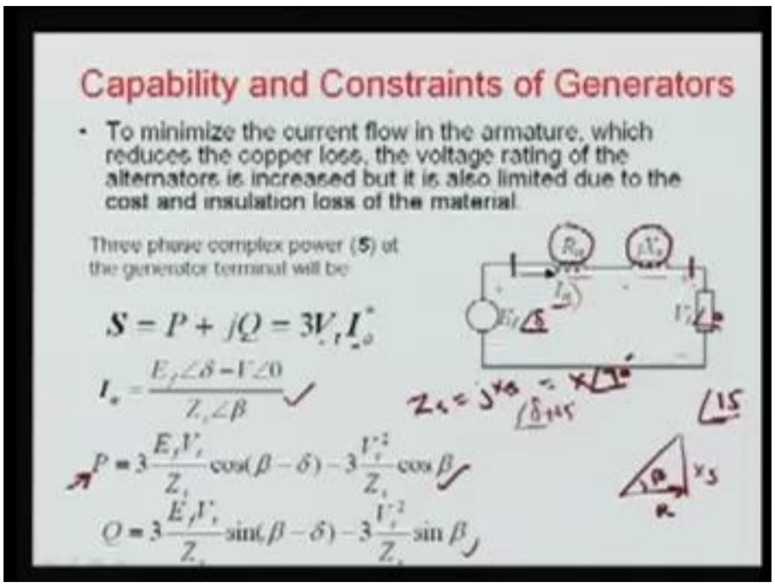

Now this terminal voltage that is the voltage of alternator which can be seen here; this is your terminal voltage of alternator. So, the reactance is an E f just we have written; this is your equivalent diagram of an alternator. Now this rotating whole rotating mass can be represented by this equivalent electrical circuit, where this E is the field emf that is again depends upon the field excitation level this voltage, then this current I a that is your armature current, and it is flowing through the winding resistance. And this x s has two components; **o**ne is the leakage this actual inductance of the coil and due to this armature reaction component. So, it is called synchronous reactants.

And this is your terminal voltage, and then we have let us suppose one load, and load may be the transmission line those are carrying power. So, to minimize the current flow in the armature which reduces the copper loss, the voltage rating of alternator is increased but also limited due to the cost and the insulation cost of the material. So, this voltage as I said is limited due to the cost; we are having the insulators those can sustain high voltage as well. But still it will be very expensive. So, always we engineer try to design a system that will be the techno economical as we can say. So, the cost should be minimum, and the performance should be better.

Now let us see this is again equivalent circuit of the cylindrical rotor type of alternator synchronous generator. We can write this three phase complex power S, I had the generator terminal here. It will be your terminal voltage this here I have represented at the single phase. So, this current conjugate means three times the voltage, it is a phase voltage multiplied by current which is flowing here and that is a conjugate of this. So, we can write this current I a armature current here this voltage minus this voltage divided by the impedance. So, we have written here E f; here we have written here the delta.

Taking this voltage as a reference here, we have seen that this E f is having some angle delta. Now you should be very much careful, and you should know what is this delta. This delta is known as torque angle or sometimes power angle, because this is the angle between the two voltages. Means it is a terminal voltage and this is your field voltage. So, this is called load, angle and it is a different than your power factor angle or insulation angle.

So, this angle as we know the power factor angle is nothing but the angle between voltage and current; however, this load angle is between the two quantities of the same unit means the voltage and voltage, current and current. So, this is delta that is with reference to this voltage zero. If we are taking here let us suppose 15 degree of this voltage, then here this will be your delta plus 50. So, this is basically I can say with reference to this terminal voltage, this angle delta that is the power angle.

So, we can write the current which is flowing in this voltage that is voltage E f angle delta minus this voltage divided by the impedance here which I have written here. If we will put this value here and you will take real and imaginary components separately, then we can see the real power at this terminal here p will be nothing but three times E f V t upon z s cos beta minus delta. Here the beta is the angle of here. Means the angle if we will say this is your R; this is your x s, this is R. So, this angle is your beta. So, this is called also impedance angle. So, the real power can be related as this expression, and the reactive power can be denoted as this one.

We know that this x s is very very high compared to the resistance of the winding, because normally we use the very pure conductor. Conductor means we use aluminum or the copper; normally we use the copper in machine winding. So, the resistance is very very less. So, what we can do? We can see here this z s, we can simply write z x or we can write here x angle 90. So, putting this beta is 90 degree and here z s is x s or here, what is the value.

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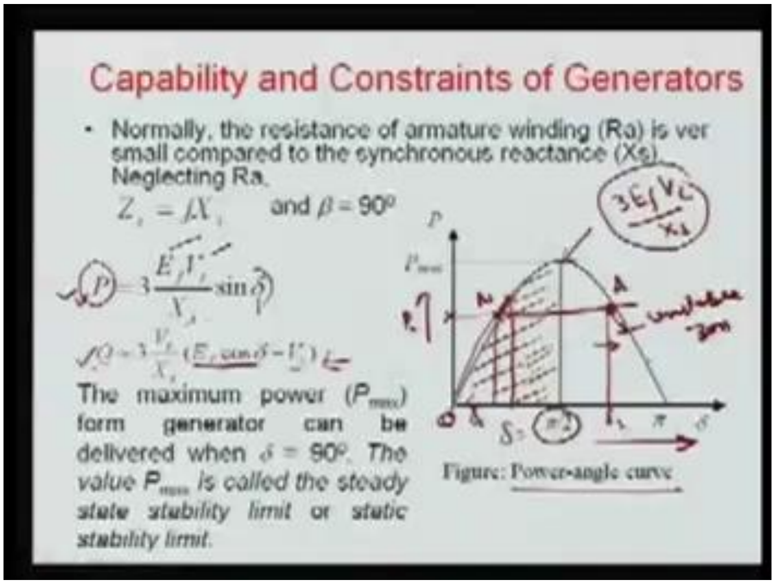

And then we can get the simplified relation here that the p will be three times E f V t upon Xs sin delta, and the reactive power we can get this three times V t upon X s E f in bracket E f multiplied by cos delta minus V t. Here you must always know that here E f and V t, they are the upper phase quantities; they are not line to line. So, per phase here this is also per phase and this we are getting the three phases because here three is coming. So, from here, you can see if we will draw the graph between the delta and P, we will get this diagram, and this is called power angle curve means here this is the variation of delta here, and here the P we are getting this sinusoidal curve.

Now this maximum value here which we are getting here, it is nothing but your three E f V t divided by X s, and this value is called the steady state stability limit or static limit. So, this is under the limit on this generator means this generator cannot produce power in steady state more than this value, because the maximum value here for the sin delta will be unity, and this unity will be only at the delta is equal to pi by 2. From this diagram, we have the two sides another side you can say. This is one side of this delta pi by 2 and this side. Now you can say for any value of p, here let us suppose any value I can say P naught, if you draw this here line means this intersection here as well as here we are getting.

Means we are getting for the power which is this generator is delivering; we are getting delta is this. Another delta is here means it is I can say delta one and delta two. Now the question arises at which angle this machine will operate? This operation here this angle is smaller, this angle is larger. We can see that this area this side is called unstable or stable zone. So, we cannot operate the generators in this zone means always our angle should be less than pi by 2, and this shaded area, it is your stable zone of the system. Now how we can say that this is stable or unstable? Let us suppose our system is operating at point A. If there is a sudden increase in the power; if some power is increased, what happens? From this expression, if the power is increased keeping this constant, we have to go for this reduction here in the delta. If we are increasing this sin delta means here beyond this angle, what will happen? If your angle is increased, what happens? You are coming here and again your power is reduced. But we want more power. So, this area is unstable, and this area is the stable. You can see from this area this is let us suppose your A 1 and that is this further power is increased, then you are here and your delta is increased. No problem, but here your delta is increasing but your power is reducing

So, it is a reverse, and that is why this zone is called unstable, and this is called stable. So, we must operate our power system in this zone that is the stable zone, and it is one of the constraints of the power system generator, where this is your steady state constraints; it is not a dynamic. And this is related to your power flow here. Now we can see in the reactive power here, as you know the reactive power is also one of the very important component of this generator which is going to generate, and that is related by this expression that is E f cos delta minus V t. So, this value will be positive if this component here is more than this V t.

This may be negative, because here V t is the magnitude positive always; Xs is always positive. So, only this sign depends up on here; however, this power is every time is positive, because that angle always starts from zero to delta; that is delta here and it is a pi by 2. So, it depends on whether this Q is negative or positive, and it also known as whether it is over excited or under excited.

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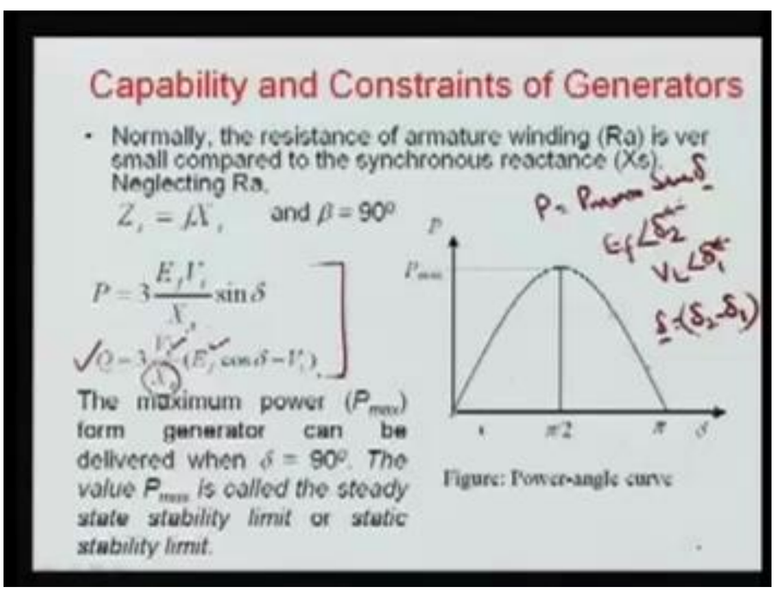

So, in this expression that is the real power that is P that I said it is your now I can write this real power P in terms of P max sin delta. This delta is basically the difference of the voltage angles of the two buses means here for example just I represented the system here. This is your E f, and this your V t. So, it is the voltage angle difference between these two points means here if we are going to use like your E f, I said it is your angle delta, and terminal voltage was zero. So, this is the difference between these two angles. If it is not a reference value, so this delta is the angle difference between these two voltages.

Means if this is let us suppose lambda two, this is lambda one. So, this delta will be nothing but your delta 2 minus delta 1. So, this is the voltage angle. Now again you must be very careful, and this delta is your load angle; however, this angle delta two and delta one are the voltage angles, both are totally different. So, the difference of the voltage angles is your load angle or between two adjacent buses. If the system or the element is connected in between two buses, then it is the difference of their voltage angle is your load angle.

Now let us see the reactive power which is related with your terminal voltage, excitation voltage and you have this X s. It is basically this expression is only valid for cylindrical rotor generator or motor means it is equally valid for motor as well as the generators means it is for the cylindrical machine I can say.

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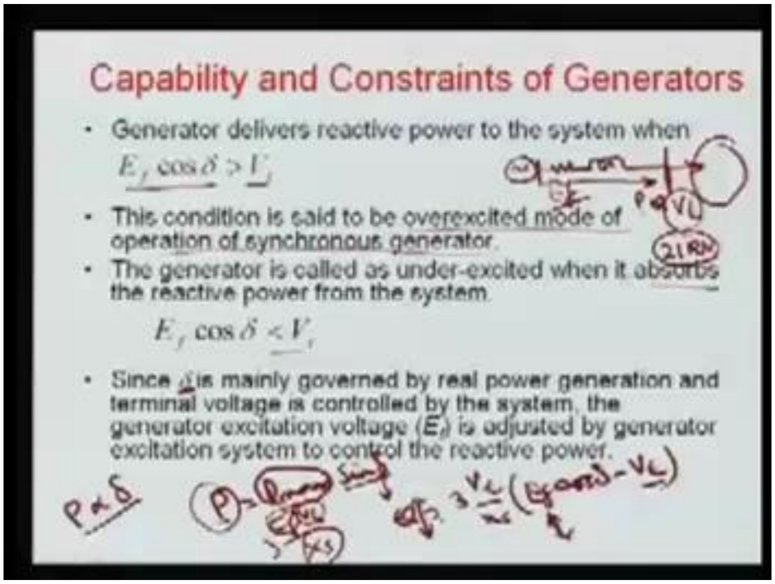

So, the generator delivers the reactive power to the system when it is more. If you remember here in the previous, it is your terminal voltage, and it is giving to the load. So, this is nothing but your R; this is your X s, and this is your alternator which is giving feeding power. So, we calculated here this P and Q. So, this P and the Q is the injection of real and reactive power at the terminal buses. So, here P is every time positive, since, it is a generator, and this generator received power from the turbine in terms of mechanical power, and then it is converted to the electrical power through this alternator.

And finally, it is flowing to this bus and then it is no doubt it is your system. So, from the previous equation, we saw here this value is positive. If this value E f cos delta minus V t is positive; otherwise, it is negative. So, I can say this machine will deliver reactive power or injects the reactive power when E f cost delta is more than V t. And this condition is said to be overexcited mode of operation of the synchronous generator means it is overexcited means this value E f is more than is your terminal voltage; it is called overexcited.

The reverse is under excited where this E f cos delta is less than your terminal voltage, and in this case, this generator absorbs the reactive power form the system. And now especially the absorption of the alternate reactive power by the alternator is normal case; it is not allowed unless until there is some specific need. So, we can see one very good relation that we saw that our real power P here your P max, here sin delta and your reactive power; it is your we had the three if we will see that is your three times V t upon X s, here E f cos delta minus your V terminal.

So, this delta is the governing criteria for this real power, why? Because this P max which is dependent on the terminal voltages, multiplication of the terminal voltage and the excitation voltage? So, we have a limitation on this terminal voltage as well as the excitation voltage. Why we have the limitation on the terminal voltage? Due to this again, the insulation of these alternators where the winding are put; so as I said, we cannot more than certain terminal voltage if your insulation is for particular voltage level, then this rating is decided based on that.

So, if your alternator is rated at 21 KV, then we cannot exceed more than that this voltage; only we can allow certain percent that is not more than plus minus 10 percent in any case. Normally, it is not more than plus minus 5 percent. So, we cannot increase this. Similarly, here the excitation voltage, this component is nothing but your V t divided by X 3. So, you cannot increase much; you cannot here increase much; you cannot here increase at all; you cannot change. Once winding is constructed, axis is fixed. So, the only option here if you want to change the P, you have to go for the change in delta.

So, we can say this P is directionally proportional to delta, because sin delta if delta is this small value. So, we can write sin delta as delta. So, the real power is mainly governed with your delta, or you can say delta is mainly governed by the real power generation. And the terminal voltage here is controlled by the system; the generation excitation voltage E f is adjusted by generation excited system to control the reactive power. Means to generate this reactive power or to absorb, we can only change this E f which is in your control.

So, this V t is here the system voltage; you have connected this voltage you may not control. It is very difficult to control this voltage, because this voltage depends upon the system voltage, and what is the reactive power injection, etcetera. But this E f, it is very easily you can control, and that is your excitation voltage means excitation that you can change the excitation; that is here fill voltage basically nothing else. And by that, you can control this. So, the reactive power generation and absorption, you can control very effectively by changing your E f.

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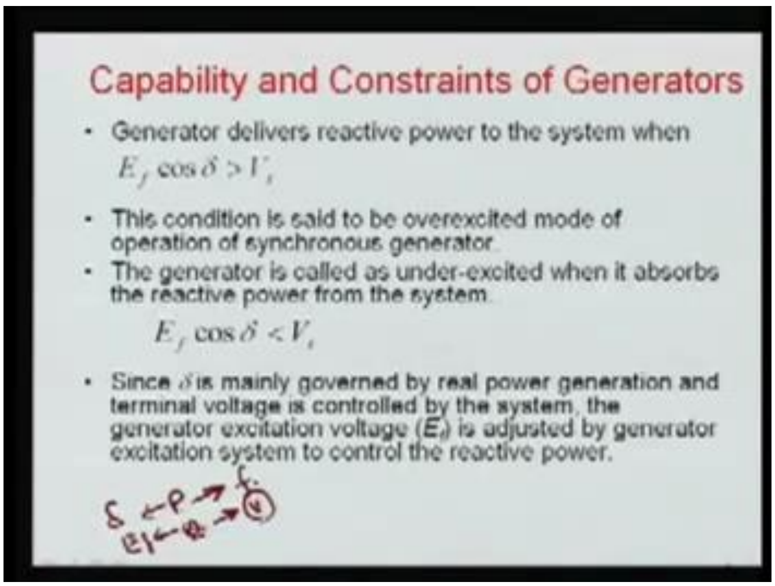

So, this delta which controls the real power means the real power here, we can control by changing the delta, and this delta is basically changed by you cannot change the delta by yourself. Delta can be only changed by changing the input to the turbine. So, this delta is changed by the turbine input power, and therefore, we can change the power, and this power changes the frequency of the system. So, we would normally this real power controls the frequency of the system.

However, the reactive power which you can change in the alternators by changing the excitation, and this reactive power change the voltage of the system. Means how much reactive power you are feeding and based on that the system voltage profile will be affected. So, this real power is directly governed to this you can say delta. Delta changes the real power, and therefore, the frequency, and here your excitation voltage will change your reactive power, and therefore, the voltage of the system. So, these are basically the couplings; normally we call the coupled that is your P delta coupling and the Q v coupling or we can say P v d coupling and Q delta d coupling. So, these are that basically used in the load flow analysis and other things.

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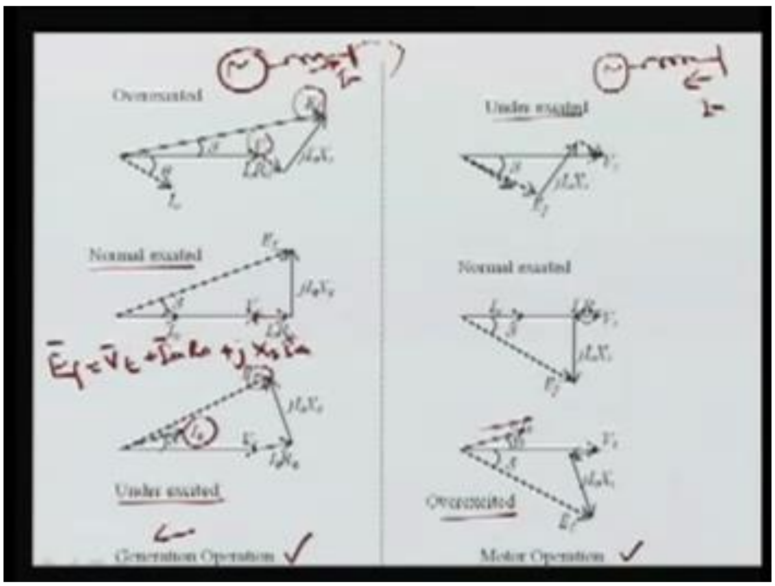

Now let us see again the phasor diagram for the over excited and under excited in the different modes; as a synchronous machine, it can run as alternator; it can run as a motor operation. So, in the over excitation mode, here if the current is lacking means current is lacking behind this voltage terminal voltage, then you can see your excitation voltage E f is more than your V t. So, when the current is lagging and we can say here it is your alternator; this is your reactance, and this is your terminal voltage. And here we are talking this current which is going inside this system that is we are system connected.

However, if it is in phase this current in phase with this voltage, this is called the normal excitation means phasor equation will be we can write this for the generator, E f will be V t plus I a R a plus j X s I a; anyhow here these are the phasor quantities. So, now we have written the phasor diagram this V t plus I a R a and here with the J sign, here this is added. So, this will be E f. In under excitation, this current leads the voltage; that is the terminal voltage of alternator. Then here it will be addition here, and you can see it may be less than your terminal voltage of this here.

So, this is your under excited operation of generator. In other words here in the motor operation, just it is reversed means if your current is lagging, then it is called under excited; if your current is leading, then it is called over excited, why? Because this is your motor, and then this current is coming out from the system; here it was injecting, here it was coming out. So, this sign is changed. So, here in the under excitation if it is lagging, then it will be under excited. However, it is lagging here, it is over excited, because it is injecting. And this similarly we can say if it is in phase with the terminal voltage, then it will be normal excited, and if it is leading, then it is called over excited of the operation. This is the motor operation; here it is generator operation.

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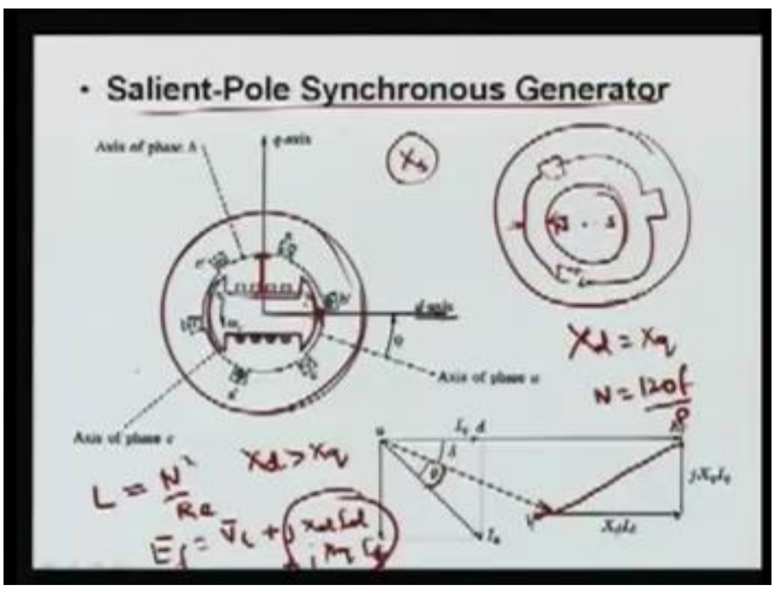

Till now just I discussed about the cylindrical rotor machine; we saw this over excited and the under excited for the motor and as well as the generator operation. Now this is the diagram of salient pole synchronous generator. This is your I can say it is a stator; here this is your stator. This is the rotor, and it is some sort of salient, because here it is not that. In the wound rotor, what will happen? This is your stator where we will have the winding. So, here it is winding will be it cut rotors flux basically and here we have the three winding, and this rotor will be here circular.

So, this is your cylindrical; this is your salient pole type because the pole sequence, this is a salient it is outside. The major difference here that in terms of reactances, because this is a circular, so the air gap here between the rotor and the stator is almost constant through the air. Here you can see this is very small. So, this is constant; so, what is happening? That we are going to have X s; here it is fixed, and it can again this is pole basically. It is the field winding where we can have a formation here N and S; again that can be obtained by having the winding on the rotor.

So, here you can say this air gap is uniform, so that is why the reactance between the stator and rotor is the constant. But here in the salient, you can say the air gap here, it is more up to this value, and here it is very small. So, in the d axis, it is called the pole; this is if it is your north pole, this is South Pole. Then this is called the field axis and the d axis is said that the North Pole to this stator and this distance is very small; what does it mean? If this distance is small means this L corresponding to this axis will be more or we can say it is we know this L is N square upon R. R is the reactance and that reactance here if air gap is less means reactance will be less.

So, what is happening? This X d here is in this case X d is more than your X q means reactance to the coordinated axis where air gap is more. But in this case, whether it is X axis or d axis, it is same that is your cylindrical synchronous generator. Since, we have the different reactances along d axis and q axis, then we can have the phasor diagram, and then we can have the currents in terms of d axis and q axis current, and we can draw the phasor diagram. So, let us suppose this is your terminal voltage; this is your current which is lagging with the power factor angle theta.

This is your terminal voltage, then this current can be decomposed into two components. One is your d axis component; another is your q axis. So, this is your d axis current; this is your q axis, and then we can add together; here resistances are neglected. So, we can have here this current id multiplied X d will be here and then it will be this one. So, what is happening? We can write here for this generator E will be that is E f will be your V t terminal voltage plus I can write j X d I d plus your j X q I q. Means here we are adding some basically what is happening here this is your if you see the equivalence impedance of X d and X q, we can have V t some plus addition here we are adding.

So, this is not equivalent diagram; it is a phasor diagram of the salient pole synchronous generator. And this generator is used in the hydro generators because we can go for it is only two pole machine. We can go for the several pole machines and then speed will be changed accordingly. We know this speed that is in rpm, it is 120 f upon P where P is the number of poles. Now in the previous section, we saw that this real and reactive powers; it is only a term of axis that is appearing, but now we have the two reactants that is X d and X q and then we can have the expression.

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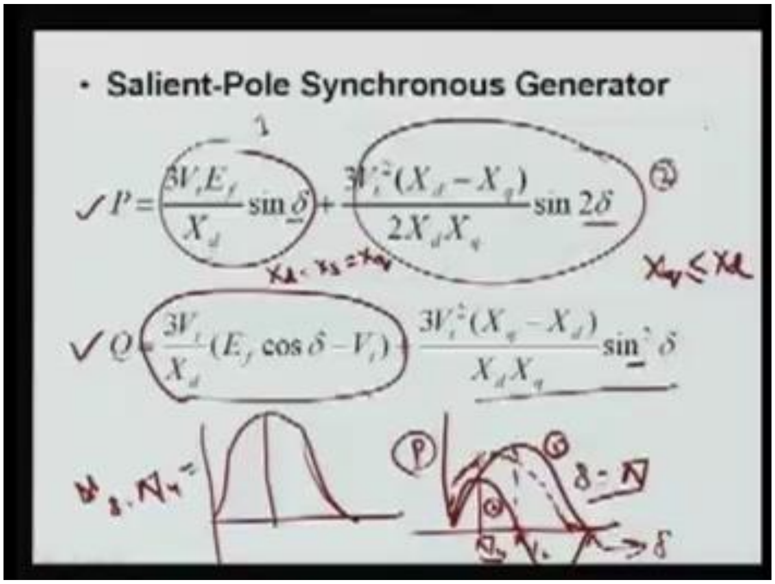

And we can derive in the similar fashion, and we can find the real power P for this generator. This is your generator; here we have a reactance, and this is your terminal voltage. So, here we are having the two reactance’s that is your X d and X q. So, the real power is three times V t E f upon X d, and we are having another term here. That term is your three times V t square X t minus X q divided by 2 X d X q sin two delta. Now from this expression, you can see we got the similar type of expression here in the cylindrical rotor. Means X d if X d is equal to Xs and that is equal to X q, what will happen?

This term is now X s and here X d minus again X d if it is equal, then this term will be zero, and this component will vanish. But in this case, it is not equal; this will be different than this. So, we are getting another component, and now you can see this component is two delta here sin two delta here is the delta. Means if we draw here this diagram earlier, we had our P angle; this is for your delta; this is your pi by 2; this is a pi for this two delta. Means here your pi by 2 means here pi it will be your zero means here at the pi by f4, what will happen?

At the pi by four delta, this component will have the maximum value. So, what we are going to get? We are going to get another component like this here. So, this component I can say component number one and component number two. So, this gives the diagram for the component number two and this is for component number one. So, that resultant here if you want to draw, then we can have here. This will be now added, and this is shifted slightly and then we are going to have here slightly this one. So, this angle is slightly shifted; this is not pi by 2, it is less than that pi by 2.

So, this is the real power of our salient power machine. So, if we can keep anyhow this is very close to this, then this power we can have the perfect sinusoidal here. The power sinusoidal means the power here P, and here this we are drawing this angle delta that is your load angle. So, this is the term this is you can say generalize; from this expression, we can generalize the wound rotor by putting X d is equal to X s is equal to X q and then this term will be minus.

So, it has the double frequency than this first component, and your resultant will be added together, and it will be tilted. So, this is your real power. Similarly, for your reactive power, you can see now we had this component earlier as well in the cylindrical rotor, but now we are going to get another component. Here this again it is delta but we are getting sin square term. So, the reactive power here it is added together, and now you can see this is X q minus X d means here this X q is less than X d. These are the positive quantity. So, this X q is now going to be reduced.

Here this P is going to be increased slightly in this zone; up to here, it is increasing, and here it is decreasing means this is your pi by 4. So, this value means here if you draw the resultant here, it is slightly I think it will be here maximum, and here it will be zero somewhere early. So, we cannot go for even though pi value is here pi is equal to delta is equal to pi. In this case, it is less than that but till delta pi by 4; this P is increased due to this component. But here the reactive power, you can see this component is the negative, because this X q is always less than or equal to X d.

So, it is basically reduced in term. Here this is always positive; this is positive; this is positive. Terminal voltage is possible and then we are going to have this. In this case also if we can put this X d is equal to X q, then it is nothing but this whole expression comes to be this first term only, and this is vanished out. Means we are getting again wound rotor, where X d is equal to X q. So, this is real and the reactive power expression and that can be derived similarly to this wound rotor machine and without any general loss of generating.

So, we have seen that modeling in terms of your synchronous generator as well as the synchronous generator of two types; that is the wound rotor and salient pole machines, and we saw this limitation.

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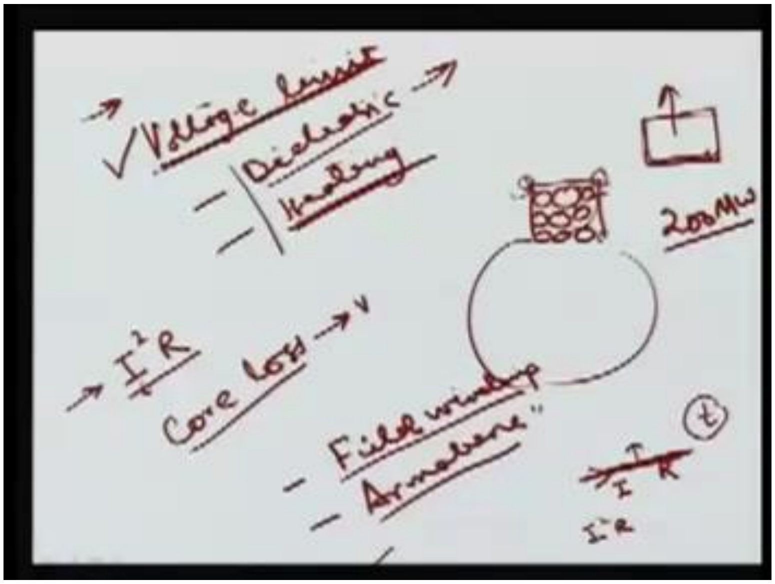

First limitations arise in terms of voltage limit and this voltage limit here I can say this voltage limit is basically of the two regions. First one is due to the dielectric means dielectric that we are using this insulator dielectric and another due to the heating. So, we cannot increase the voltage excessively that the dielectric material which is there may not sustain and also it may not be economical also due to the heating. Suppose, here we have the slot where we are just putting the winding; here we are putting the windings various different conductors are there we have placed in this.

So, what happens at these corners? We have the excessive field, and therefore, more eddy current that is flowing in this core; this is basically your rotor and the stator as well. So, what happens here there is more eddy current and the more loss. So, if you are going for more voltage these more flux and more here stress will be there and there may be heating and that is not desirable. So, the maximum continuous limit due to the excess flux is lower than that breakdown consideration; therefore, the limit due to the axis flux is the determining limit. The flux in it is affected by the frequency that is the core flux is proportional to the voltage and frequency.

So, this core heating means we have the two type of heating. But this voltage limit that we cannot go for higher voltage; the heating here we are discussing, this is due to the flux or we can say the core heating that is due to the core loss. Means we have the two loss; one is your copper loss that is i square R loss, and another is your core loss. This core loss we know it depends on the voltage that is here related to your voltage. So, no doubt if we can rise the voltage, this current will be reduced, but this loss will be reduced, but this loss will be increased.

So, we have to see that how much loss how we are going to heat the core of this insulation material and how we are going to dissipate the heat which is generated in terms of core loss. So, the voltage limit of the alternator is due to the dielectric that we should have the cheap dielectric material that can sustain these windings, and there should not be any fall from this here; it is core that is outside the yoke. And here the heating due to the excessive flux that is at the sharp edge especially, it is very high, and therefore, more eddy current and there will be more heat and there may be some hottest spot.

And there is a possibility that this insulation will get damaged, and that, therefore, there will be a fall; it is a short circuit fall line to ground fall and that we do not want. So, this is your voltage limit; another limit is basically that is called the capability limit of alternator, and that depends upon the various heating inside and due to that i square R heating. So, we have the field; we have the field winding. So, we can have the field heating, and we have your armature winding, and then we can have the armature heating. Another is called end zone means due to this corner and sharp edge, another limit is your heating limit.

So, with these heating limits our generator should operate in those boundaries that we should not go for more than its allowable permission heating limit. Basically, this heating again depends upon how you are going to cool means if you are cooling system is very very strong; we must always know why this heating is very important. Suppose, here this wire is going on here and there is some current flowing i means here this loss of this binding if R is the resistance, then loss will be your i square R, and this power is converted in terms of heat.

So, if you have just heat which is dissipated from this conductor, continuously we are dissipating heat. So, the temperature of this body is maintained at particular temperature, but if this heat is not dissipated means heat generated is not taken away, then the temperature will keep on raise, and excessive temperature of the wire may lead to several problems. So, this is true for any material means whatever the heat is generated here if it is transmitted outside, then we can say we can maintain the temperature. So, it is basically the heat which is generated in terms of due to the loss; if we can take it out properly means there will be no increase in the temperature, and therefore, we can operate successively.

So, it has some temperature limit; this generator cannot more than certain prescribed temperature. Otherwise, there will be the insulators, here insulations, etcetera will get damaged. So, we must provide the better cooling, so that whatever the loss is going to occur in terms of here in the generator that must be taken. So, that is why for high rating power generator where there will be more loss, we go for the very better and better cooling; that is we go for the hydrogen cooling. We can go for the water cooling; various types of cooling scheme, and again, the performance depend upon that.

Means if your generator is rated at 200 megawatt and if your hydrogen phasor is reduced, then you cannot operate even though this generator at 200 megawatt, why? Because this loss which is occurring, it is not dissipated; it is not taken out from that you can say the air gap of this alternator. So, we have to operate at a lower speed lower power. So, if alternator cooling is not so strong, then you cannot operate at its rating. So, normally in the alternator generator power plants due to some reason if the hydrogen pressure is reduced, then generator is reduced means its capacity is reduced, and that reduced rate it is normally generate the power.

So, the cooling is very important, but still the cooling once it is decided, then we should operate this generator in its capability limits. So, the various type of capability limit that is your field as well as your armature and field heating limits which I will discuss in the next lecture. And then we will form one zone, and then we will see this is your basically operating where this is also known as the capability curve in terms of real and reactive power. We will see how this in terms of real and reactive we can draw one zone, and that zone is basically the operating zone and we also call it the capability curve of synchronous alternators which we will see in the next lecture.

So, to recap here, we have to see the limit; the two limits we have seen. That is your voltage limit, and we have also seen that steady state limit of the alternators. We saw the two types of alternators; one is your wound rotor, another is your salient. Salient pole type of generators are used for the hydropower generator where we rotate these generators at the lower speed, because the hydro turbines are efficient at the lowest speed whereas in the turbo that is the terminal power station; we operate these alternators of very high that is maximum speed, so that we can achieve the higher efficiency, and those turbines and thermal power stations, they are more efficient at the higher speed.

So, we keep the pole as minimum as possible that is two in number and then speed we achieve that is 3000 rpm for 50 hertz. So, this is the basic reason that the thermal power station alternators they operate at high speed; however, the hydro, they operate at less speed. Again in hydro, the speed keeps on changing; in all thermal power stations, the speed is same that is 3000 rpm. But in hydro, it depends again that how much energy do we have, how much hertz that is having that is water head, so that you can discharge that energy. So, for hydro power station, the number of poles is varying from station to station means the speed of rotation of turbine also keeps on changing.

So, in next lecture, we will see the various limits that is filed heating limits, armature heating limits, energy heating limits, and then we will derive the capability curve of alternator. And then we will also see the capability of the transmission line and the transformers as well. Thank you.