Introduction to Smart Grid

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Lecture - 10
Distribution Generation resources- IV

A very good morning to all of you, so in this lecture we will just continue our previous lecture about the fixed speed wind turbine generators.

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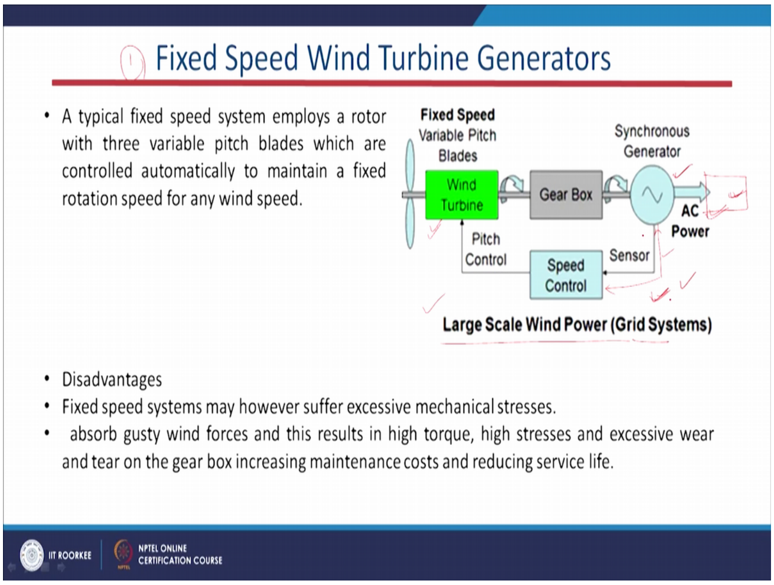

If you could see this block diagram of the fixed speed wind turbine generator, here we have the wind turbine, and we have gear box and we have the speed control mechanism, and the synchronous generator. And with this arrangement, we can achieve the electrical output from the generator. But however, here the power electronics interfacing devices are not present.

So, because here it is a fixed mode type of wind generation system and, of course, we have this speed control mechanism with help of this sensors, we can sense the speed of the generator, and the speed can be send to our wind turbines structure, where we can control the speed I mean the pitch angle of the turbine and so, that we can maintain the synchronous generator speed constant.

And what are the disadvantages of this type of winds generating system. The first one is the fixed speed systems may suffer excessive mechanical stresses, that is the first disadvantage. And the second one it absorbs the gusty wind forces, and this results in high torque high stresses and excessive wear and tear. So, this is very very important that it has the excessive wear and tear. So, the maintenance cost increases on the gear box basically, this stress and the wear and tear mechanism basically is on the gear box. So, that is why the maintenance cost increases here, and reducing the service life also due to this wear and tear concept the service line of the equipment also reduces. So, these are the disadvantages of the fixed speed wind turbine system.

After that there is a change basically from the fixed generation systems, we have moved to variable speed wind turbine generators. Why this variable speed wind turbine is necessary as you already we have seen that during the fixed generating mode, we have basically different types of disadvantages, we have like wear and tear and stress is also there on the turbine section.

So, to overcome those disadvantages, we have the variable speed wind turbine generating systems. And what are the first advantage of this particular system, it will just cope with stormy weather conditions as all of us know that the wind system is very intermittent in nature. The wind speed the wind velocity can vary from 2 meter per seconds to 16 or 22 meter per seconds throughout the day. So, in that case if the wind speed varies. So, accordingly our system should cope and then only our system is going to be called as robust or stable system.

That is why we have this variable speed generator, that system is ready. Now, it is also in operation and it can cope, it can assist us during the stormy wind conditions.

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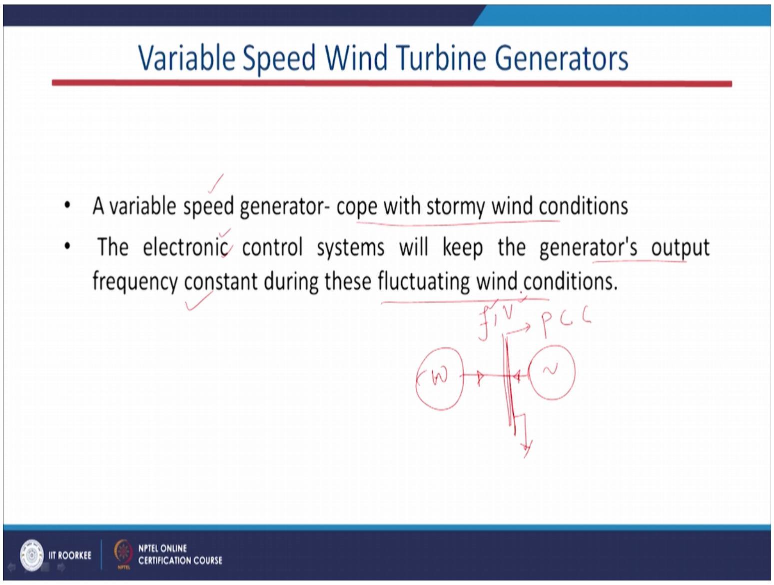

And second one that we have the electronic control system is present here, in case of fixed mode of operation as I said as I mentioned that we do not have the electronic interfaces, but however, in case of this variable speed wind system. We have this electronic control systems the electronic interfaces are basically present. And this system this electronic control system will keep, the generators output frequency constant during the fluctuating wind conditions.

Basically what happens when the wind system if this is our wind generator or wind a generating system, it is connected to the grid. Now, this is the basically the point is known as PCC just like our solar system PCC means the point of comman coupling, the where this wind generating system is connected to the grid system.

Now, we have to maintain the frequency and voltage of this particular PCC at constant, at the desired level or at the nominal values. So, for that purpose this electronic control systems, help to maintain this frequency and voltage at the desired level or at the desired values.

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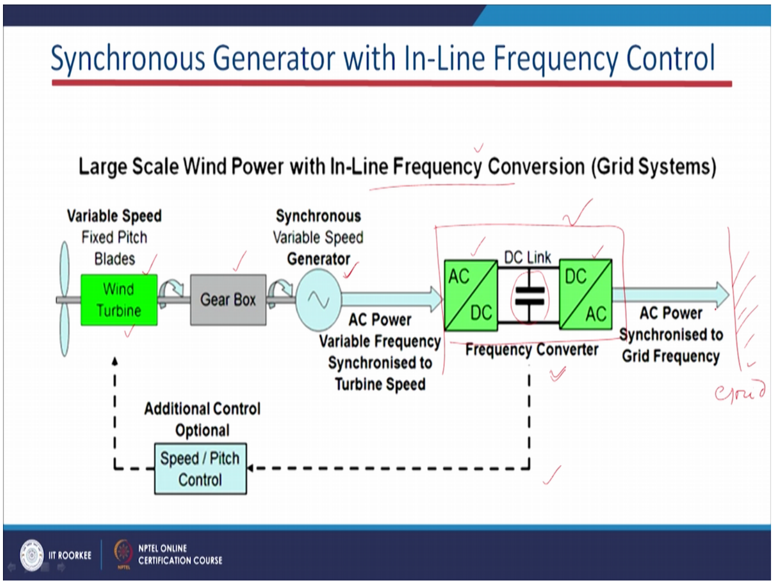

This is how this variable synchronous generator based wind systems looks like, here we have the variable speed fixed pitch blades, or we have this wind turbine section. And after that we have the gear box.

And further we have this synchronous speed variable speed generator and, after this is the extra part which is added here, this is our the electronic convertors. The first part of this electronic convertor is this rectifier, which converts AC to DC and the second part of this electronic interface is this it converts that is our invertor section, which converts the DC to AC power.

Now, we have the DC link with help of this DC link the two convertors basically connected with each other. And of course, during the operation this DC link voltage should be maintained at the rated values, to maintain the push the power from one side to other side.

Now, if you could see in this particular block diagram, the electronic convertors are basically connected between our grid system, this is our grid system this is our grid system, where this wind energy system is connected. And we have here the whole variable speed here, actually this is kind of large scale wind power in line frequency conversion system, this is a very important a why it is inline, because the total amount of power, which is generated by this synchronous generator is fed to the grid system. So, the frequency convertor or these powertronic convertors; the 100 percent power is basically flowing through this convertor section and, it is reaching to our grid section, that is what inline frequency control type system.

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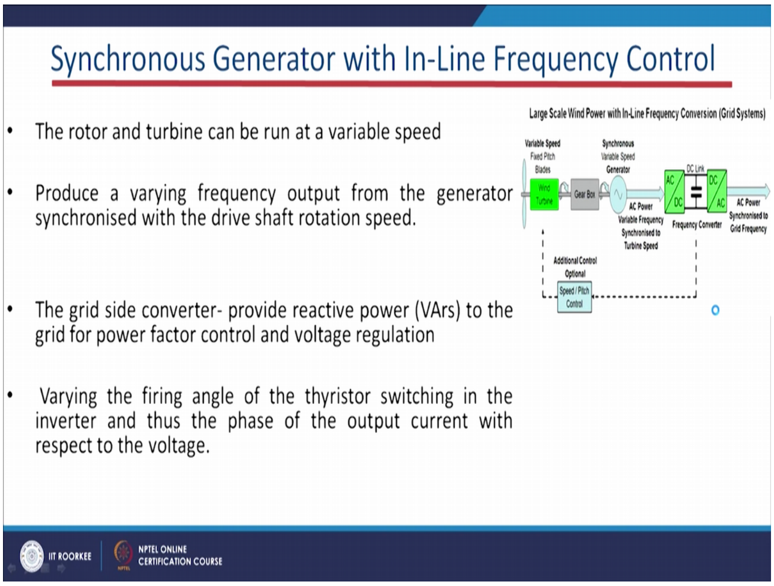

This is how it operates you can see here, this rotor and turbine can be run at a variable speed, this rotor and turbine of the mechanical part of the wind system, it can run at a variable speed. And to produce a varying frequency output from the generator, synchronized with the drive shaft rotation speed.

This basically the output if to have this a varying frequency output, basically the generators is synchronized with the shaft rotation speed. And the grid side convertor, if you could here we have like a invertor here, we have rectifier here. And this grid side, invertor it helps in providing the reactive power to the grid and, also it controls the power factor and voltage of the grid system.

These are the basically the functions of the grid side invertor, the first one is it controls basically it provide the reactor power to the grid, and also it controls the power factor, this is the power factor theta and the voltage of the grid system. Because we in the powertronics devices we have thyristors or IGBTs so, by basically the controlling the firing angle of this devices. So, we can control these quantities voltage or power factor.

Now, by varying this that is what I just said that varying this fire angle of this thyristor switching in the invertor and, thus the phase of the output current with respect to the voltage also can be controlled, basically the by controlling the firing angle we can control the phase angle between the current and voltage of the grid side, that is at the PCC basically where this wind system and the grid together they are connected.

Then third one is basically the w fade induction generator DFIG the previous model, what was the major demerit. The major demerit is that the cost of the electronic interfaces, the cost of the electronic devices are quite high its large, because this electronic devices basically they will see the 100 percent power, which is basically flowing from the wind system to the grid system.

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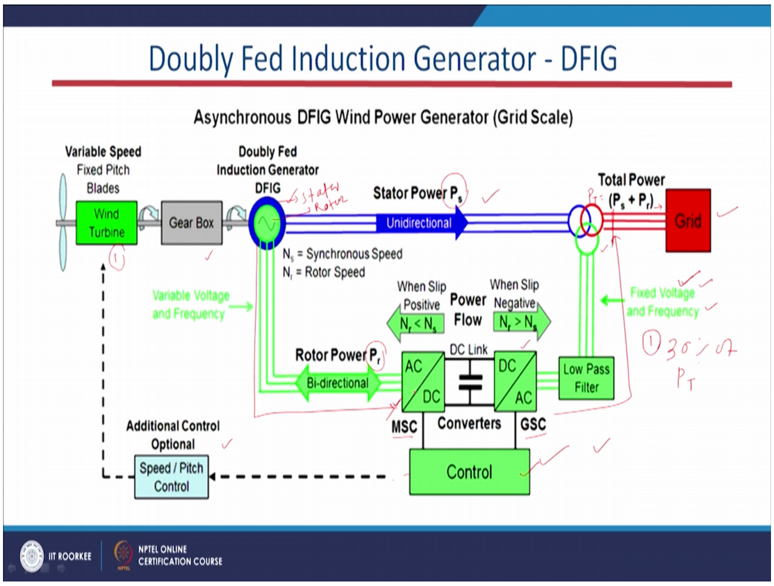

But here, in case of DFIG it is little different, what is the difference we will see that.

First of all what are the components of this DFIG let us see, the first one here is the wind turbine, which is the mechanical part again also we have the gear box. And next we have doubly fed induction generator here, we are not using synchronous generator, we are using induction generator which is called as doubly fed, why it is called doubly fed. Because it has the stator this is our stator and, this is the green one is our rotor.

Now, both this stator and rotor, either they are going to push power to the grid, or they can get the power from the grid, or only stator will push power to the grid and the rotor will receive the power from the grid side or vice versa. The point is it is a bidirectional flow of power the power will be fed to the stator rotor or it can just import or export the power from the grid. So, that is why it is a doubly fed induction generator, we will discuss more about what are the conditions, as far the operation of this particular generator is concerned.

Now, if you see here this is our stator power, which is denoted by P s and this is a rotor power, which is denoted by P r. And this is how the green person I have just shown here, this is a electronic interface system. And here we have this machine side convertor and this is a grid side convertor. Sometimes also we call it rotor side convertor and this is also grid side convertor, why it is this machine side convertor is known as rotor side convertor, because the input to this convertor is from the rotor, not from the stator. That is why sometimes it is called as rotor side convertor. And as this particular convertor is connected to the grid to this side., so that is why this is called as the grid side convertor and finally, this P s plus P r the total power is fed to the grid, basically this stator power and rotor power are added and, if the total power P total is equal to P s plus P r is fed to the grid.

Now, here the measure the first advantage is this electronic device cost is less, because we are just pushing 30 percent of the power, 30 percent of the total power is pushed through this electronic device, because we are not pushing the total P s plus P r. We are just supplying P r amount of power through this electronic device and, it is just reaching to our transformer three phase transformer, and then it is just going to the grid side. And as a result so, cost of these electronic interfacing devices is basically reducing.

And rest is if you will see here we have also different possibilities by just varying this firing angle of the convertors, may be of this rotor side convertor, or it may be the grid side convertor, we can always control the frequency and voltage at the PCC the point where this wind system is connected and the grid is connected.

That is our desire I mean we need this basically, without the fixed voltage and frequency we cannot connect the basically the wind system to the PCC the grid system. Because but finally, we have to supply a very steady I mean the power quality, improved power quality based supply to the customers or to the load.

That is why this voltage and frequency should be maintained fixed at the PCC and, that is which that is why this DFIG is the best option. And also we have this additional control option, where this control system can also supply the information of this speed and as well as other factor.

So, we can control the pitch angle of this wind turbine, or blades and also we have control system, which are dedicated for this convertors rotor side convertor, as well as for the grid side convertor.

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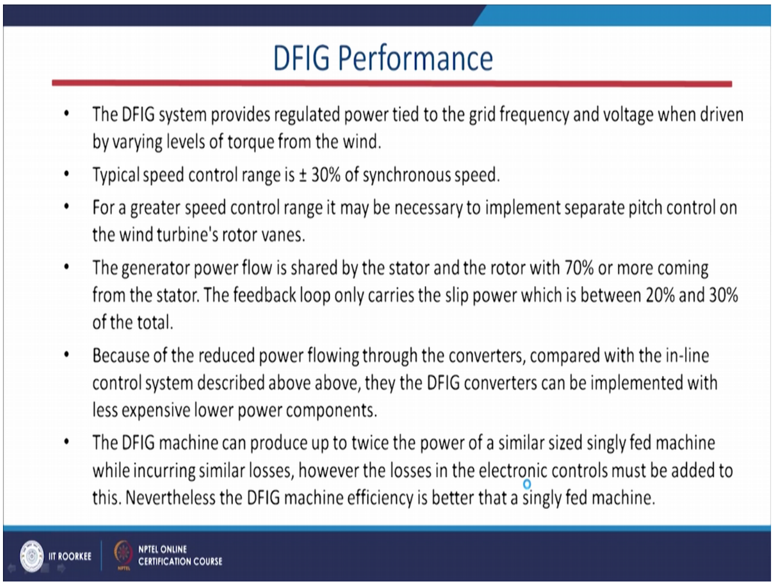

And these are some of the operational parts already I have just discussed, the typical speed control range is 30 percent of this synchronous speed. And the greater the speed control range, it may be necessary to implement separate speech control and turbines rotor range. So, there are points already we have discussed in that particular part.

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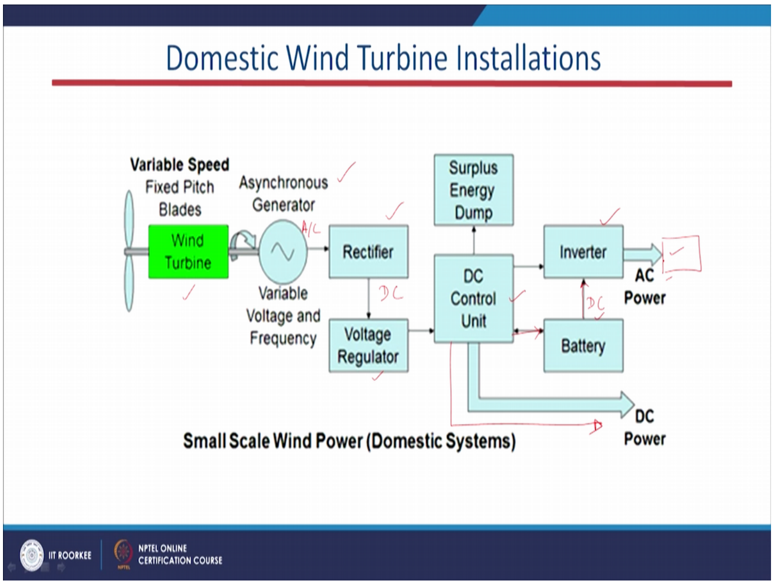

Now, this is how this domestic wind turbine structure, we have variable speed fixed speech blades and, we have as synchronous generator means it is a variable speed the I mean the frequency the speed of the generator is not fixed, that is why it is as synchronous it is not (Refer Time: 15:50) as synchronous speed, but the speed is basically varying. As synchronous generator, we have this rectifier and from the rectifier, we have this voltage will go to the voltage regulator. And we have the DC control unit, because the output of this generator is AC, and this AC is converted to DC with help of a DC rectifier.

And this voltage regulator will supply the DC, output to the DC control unit. And it will just go to the invertor section which will again convert to AC, or what will happen if we need some DC output or some loads are DC so, directly from here we can supply the DC power, to those loads and if we have some AC power AC based loads. So, from the output of this invertor, we can supply the AC power.

Again we could have some battery arrangement, because if you want to store the energy at certain point of time, if we have surplus power then of course, we can store the power using a battery system. And this is a battery so, the output of DC control unit equal to the battery. And again during the requirement period, then this battery will supply by DC power basically the DC to the invertor section and, again it will go to the AC loads.

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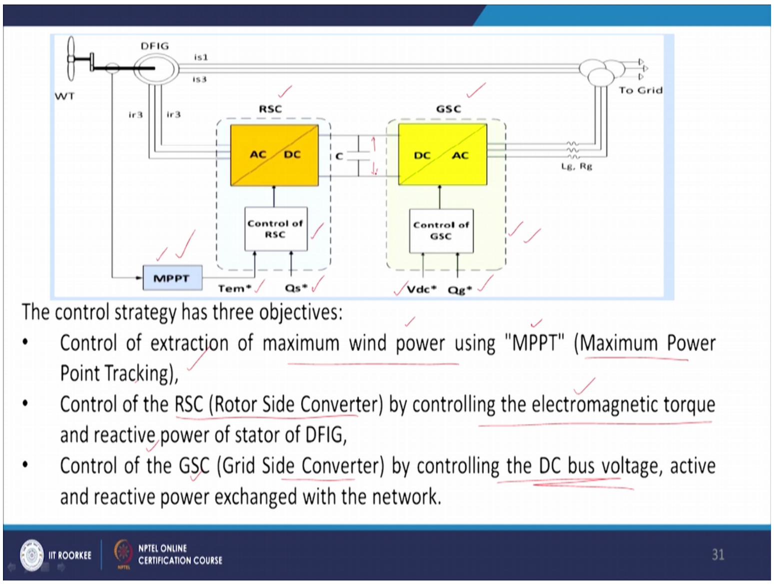

So, this is the domestic wind turbine structure. And just here I just want to say already we have discussed about this variable speed DFIG system, we have this rotor side convertor we have grid side convertor. And in case of this rotor side convertor, we have the control strategy, control strategy this control strategy basically takes, the input as the reactive power as the input and this electro mechanical torque is also another input.

Because we have to control the speed the rotor speed. So, for that we need this Q and T em the electro mechanical torque and, here in case of your grid side convertor, we have this input as the grid side our reactive power and this VDC, VDC is the DC link voltage.

And we have MPPT this MPPT is basically maximum power point tracking system. And it tries always to track the maximum speed of this wind system so, or indirectly we can say in this manner that the wind generator should operate at the maximum torque to harness the maximum power.

Either we have to basically maintain the pitch angle of the blade in such a manner that, it should just harness the maximum speed of the wind and, further this maximum speed this of the wind system, it will convert the kinetic energy to mechanical energy, again that particular mechanical energy will convert to the will be converted to electrical energy.

So that means, for to achieve the maximum power, or maximum torque this MPPT algorithms are basically are dedicated just like our solar system, we have also MPPT system, MPPT technology. And there what we do basically to achieve the maximum power that is PM from the solar panel.

So, we control this mechanism using the MPPT technology that is maximum power point tracking system. And here if you see the control strategy has basically this control of extraction of maximum wind power, the first control mechanism that is used that is the MPPT and, (Refer Time: 19:44) stands for maximum power point tracking so, the aim of this particular control strategy is to achieve to extract, maximum wind power that is our aim using this MPPT technology.

Now, second one is the control of RSC that is the rotor side convertor, by controlling the electromagnetic torque and reactive power of stator of DFIG. What is the aim of this second controller side? That is the rotor side convertor by controlling the electromagnetic torque and, reactive power of the stator of the machine. And the third one is the control of GSC that is a grid side convertor by controlling the DC bus voltage. This is the DC bus voltage this one is our VDC, we have to control this if our DC voltage DC link voltage is not maintained properly so, the power conversion from the DC side to AC side is not proper.

So, always we have to maintain the DC link voltage, at proper value at it is rated value and that is why by controlling this DC bus voltage active and reactive power exchanged basically within the network, we have to maintain at proper value. So, these are different control strategy just I have shown three here MPPT and, this is the control for this rotor side convertor, this is the control system for the grid side convertor.

In detail we will just provide references, you can go through the control strategy of this MPPT and of the rotor side convertor and the stator side convertor. So, these are some summary of operation of this DFIG system.

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Mode	Slip and speed	P_{mech}	P_s	P_r
1. Motor (T_{em}>0)	s<0, ω_m>ω_s (suprsynchrnsm)	>0 (mch delivers mech pwr)	>0 (mch receives power via stator)	>0 (mch receives power via rotor)
2. Generator (T_{em}<0)	s<0, ω_m>ω_s (suprsynchrnsm)	<0 (mch receives mech pwr)	<0 (mch delivers power via stator)	<0 (mch delivers power via rotor)
3. Generator (T_{em}<0)	s>0, ω_m<ω_s (subsynchrnsm)	<0 (mch receives mech pwr)	<0 (mch delivers power via stator)	>0 (mch receives power via rotor)
4. Motor (T_{em}>0)	s>0, ω_m<ω_s (subsynchrnsm)	>0 (mch delivers mech pwr)	>0 (mch receives power via stator)	<0 (mch delivers power via rotor)

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The first one is if our electromagnetic torque is greater than 0 and the sleep is less than 0; that means, it is negative and our this w m is greater than w s. This w m is the mechanical speed is greater than the synchronous speed and, here and the speed mechanical. The mechanical power basically is greater than 0 that means, the input to the rotor is I mean higher and; that means, it delivers mechanical power. The mechanical power is greater than 0 means, it delivers mechanical power because it is obvious, because in motoring mode the mechanical power is higher the mechanical power is the output.

And here this P s the status side power is greater than 0 that means, it receives power via the stator. If it is greater than 0 that means, it is receiving the power it is receiving power from the grid. And similarly this P r is also greater than 0; that means, the machine receives the power via the rotor.

So, in this case the machine receives this wind generator, receives both stators and rotor receives power from the grid. If it is grid this is our P s and this is P r so, both the stator and rotor receive power from the grid side. That means, it is receiving the electrical power and delivering the mechanical power. So, these are the conditions for operating this DFIG motoring mode.

Now, second one is the generating mode here, the slip is less than 0 that means, the machine speed is greater than the synchronous speed, if the rotor is rotating more than synchronous speed. So, it will just it is called as super synchronous speed super synchronism and, at that condition this P mechanical is less than 0 that means, it receives the mechanical power.

So, mechanical power is it is (Refer Time: 23:37) is receiving the mechanical power and, at that moment this P is less than 0 and P r is also less than 0 that means, the machine is delivering the power to the grid and the both the cases. If you could see here, it is just opposite the wind system is delivering power to the grid, P s and P s this is P s and this is P r.

And this is how this is how this generating mode happens and, the third one is again the generating mode, where we have this T e m is less than 0 and our in this case it is sub synchronous speed sub synchronous speed means the speed is below the synchronous speed. The rotor speed is below the synchronous speed. So, that is known as sub synchronous speed and this case also this pre mechanical less than this 0 that means, it receives the mechanical power and what is the condition for this P s and P r. This P s is less than zero; that means, it delivers power by a stator. And however, this P r is greater than 0 and that means, it receives the power via the rotor.

So, that is why it is called as doubly fed induction generator, the power can be extracted from the grid, or it can be sent to the grid side, that is why it is doubly fed induction generator and similarly the fourth one.

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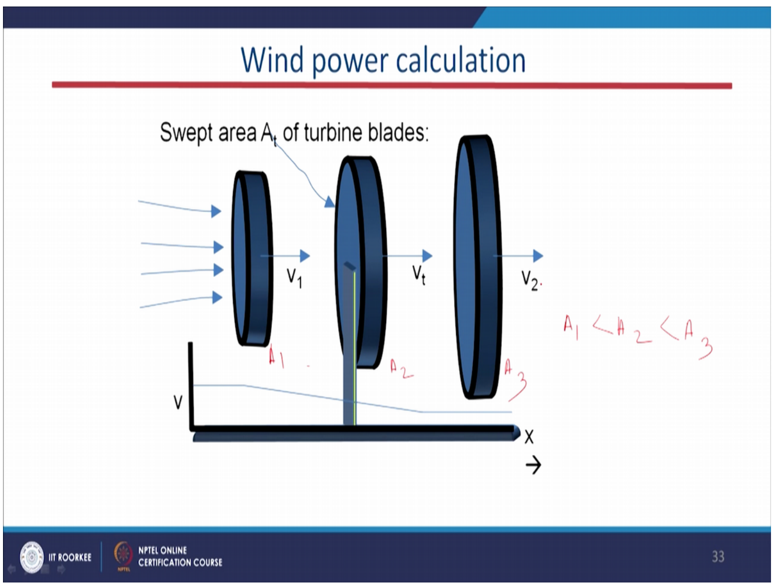

Now, we will come to the wind power calculation section here we have this structure have shown, that the swept area A t of the wind turbine let us say the swept area. The wind turbine increases area A 1 is basically less than A 2 less than A 3. This is our area A 1, this is A 2 and this is A 3.

And this is our wind speed this is V 1, V t and V 2. The swept area is nothing the area where the wind is with the wind thrust is just a fall, or on the blades of the wind turbine that is the thrust I mean the swept area.

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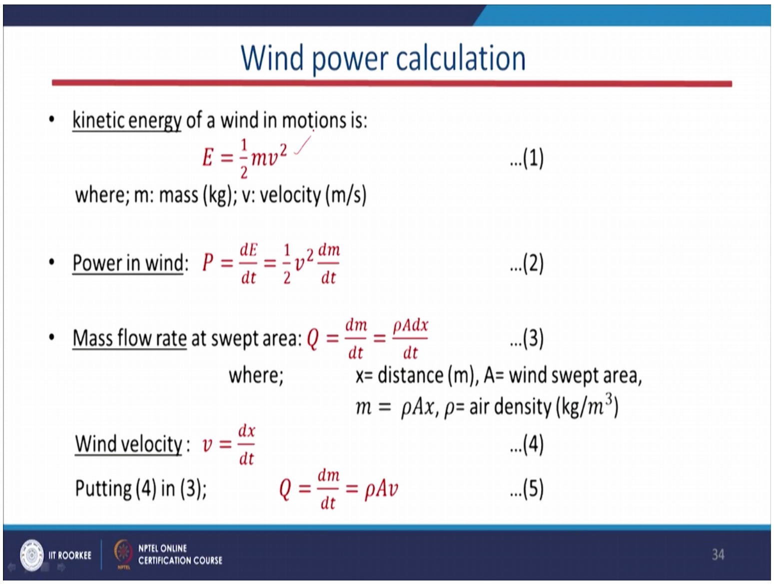

Now, we will come to the wind power calculation section here we have this E is equal to half of m v square, where this a means the air mass that is in k g and v is the velocity of the wind, that is in meter per second that is our first equation; the kinetic energy which is present in our wind, because we are interested to convert this kinetic energy to electrical energy, different using different type of technology.

So, this power in wind is how much now you know this rate of change of energies or power that is d E t by d t. So, if you just take the derivative of first equation so, you will get half of v square d m by d t, now what is the mass flow rate at the swept area this is the Q the mass flow is d m by d t the mass is m, what is mass? Mass is basically, row a d x volume into air density, row is the air density that is kg per meter cube and x is the distance in meter A is the windswept area.

Just we have discussed in the previous slide, swept area A 1, A 2, A 3 just I have shown here.

So, this A is the windswept area and, if you will just put altogether so, you will get this Q as a flow rate that is d m by d t, rate of change of mass flow, that is known as the Q and that will be row A d x by d t. Now, if we will just put again this velocity v is equal to d x by d t in equation number 3, then this q will be row A v, row is the air density a is basically the windswept area and, v is the wind speed.

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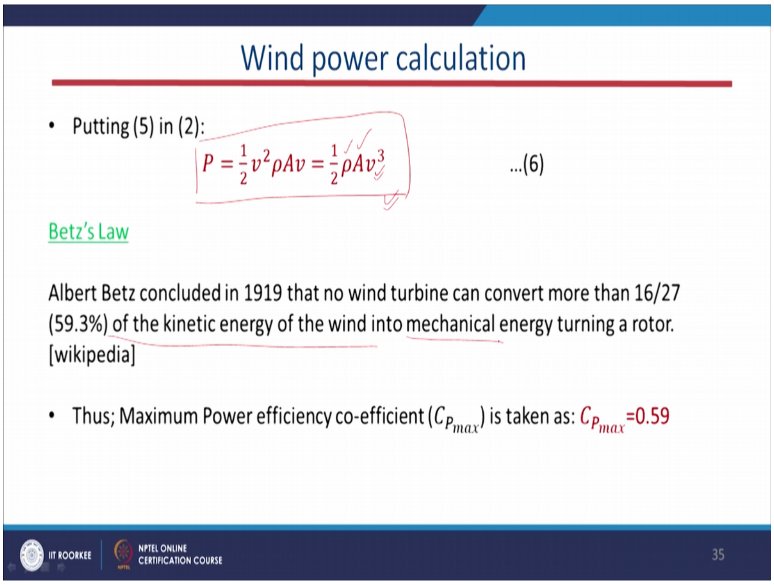

Putting all together the equation 5 into finally, the power in the wind system will get how much half row A v cube this is the very important equation. If we will just analyze this equation this power which is present in wind, it depends on three things, the first one is the row that is the air density, the second one is the swept area and v is the wind velocity.

So, these three things basically govern, or control the power which is present in wind system. Basically according to the Betz law, that he said that 59.3 percent of the kinetic energy of the wind, it basically converted to mechanical energy that is all the possible that is the highest figure we can achieve. So, that is why what this keeping in mind this figure 59.3 percent. The maximum power efficiency coefficient, the output power by input power the efficiency of the wind turbine, it will tell I can say in this manner output by input ratio will be how much that will be 0.59 and that is known as C P max that is known as the maximum power efficiency coefficient.

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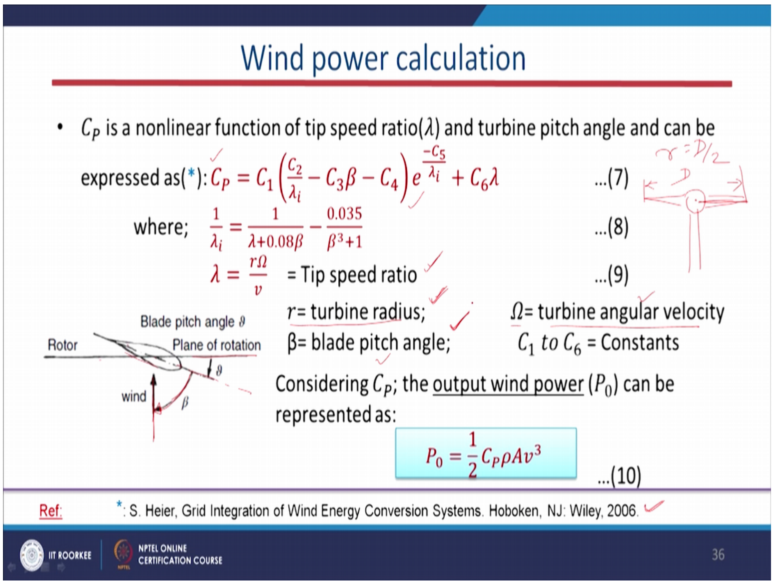

If we will see in further derivation we have given here the book reference book, where the detailed derivation of this C P's provided, if we will see further analysis the C P is a function of this tips speed ratio and the blade pitch angle and the turbine radius. So, that is why while we design this particular wind system, we are always careful for this is what is that this turbine ratio see if will see, this is our turbine ratio it will take a horizontal type of rotor structure or wind system. So, this is our turbine diameter and this is the radius, half of this d that r is equal to capital D by 2.

So, this C P is dependent on this turbine radius that is first and, second one is the blade pitch angle that is basically the beta. This beta is shown here, if this is my plane of rotation and here is the blade and, this is the axis of the blade. And this is the wind speed this is my wind speed. The angle between this 2 is basically the pitch angle beta, blade pitch angle the it is the angle basically between axis of the blade at the wind direction, between these two the blade pitch angle exists.

And third one is the tip speed ratio that is our lambda, this is basically r ohm by v, what is this r this is the turbine radius. And we have also here ohm that is the turbine angular speed in some books also it is written omega, angular is turbine angular velocity, at what rate it is basically rotating.

Now, if will just put all together so, we can get this C P expression. So, this is the expression where this you can find, that C P is directly connected to this tip speed ratio and also this turbine radius and the blade pitch angle. So, these are things they are dependent. And this C 1 to C 6 are constants.

Now, this considering the C P the output power, this P not can be represented as P not is equal to half of C P row a v Q. If you see the previous expression here, this is the we are here we are not consider the C P, it will consider the C P the output power will be half of C P row A v Q vocalized-noise] and very detail details are provided in this particular book.

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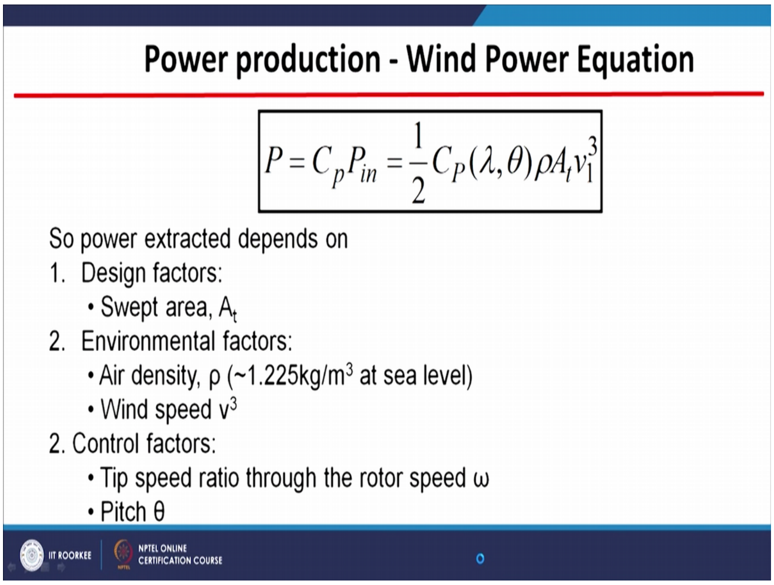

And this is how we will just see the wind power equation. The first one is this power extracted depends on the design factors, the first one is the swept area design an environmental factors like, air density that is row which is basically in general 1.22 kg per meter cube for C level.

And also it depends on the wind speed cube of the wind speed and some control factors like, we have this rotor speed omega, or I have just noted here this ohm and, here the pitch angle theta are here we are denoted by this beta. Coming to these characteristics of wind power it is like this.

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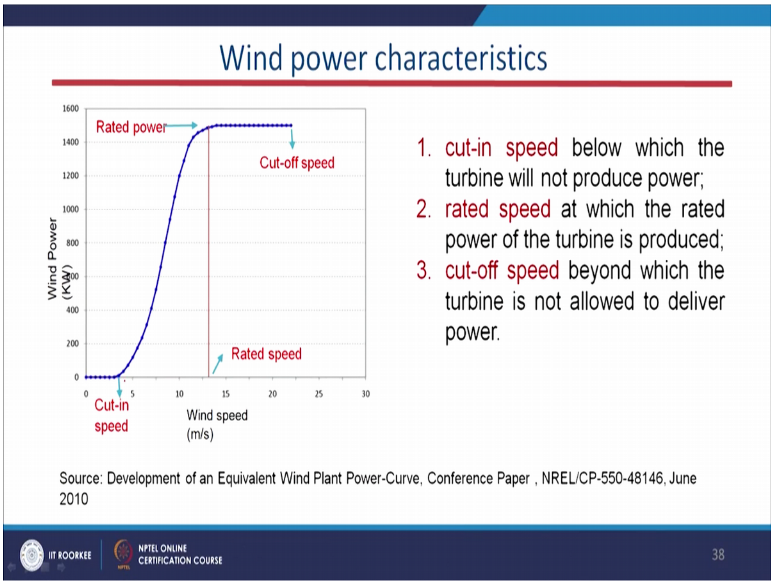

So, here the first point is the cut in speed what is cut in speed the cut in speed is that speed, below which the wind turbine will not produce the power it is the minimum speed. So, below which we cannot produce the power, the wind meal cannot produce power that is that speed is known as cut in speed. And the second one is the rated speed the rated speed is that speed, at which the rated power of the turbine is produced and, that during that period the rotor is basically safe and the machine is safe the whole system is basically in stable mode.

Now, what is the cut off speed it is here the cut off speed, the cut off sped is that speed beyond which the turbine is not allowed to deliver the power. So, we have to cut we have to stop there the machine should not operate beyond that speed. The basically it is in the range of 20 almost 22 23 meter per second and the curtain speed, it also varies depending upon the wind structure and wind state.

So, it is here almost about 4 meter per second 4.54, we can say here 4 meter per second.

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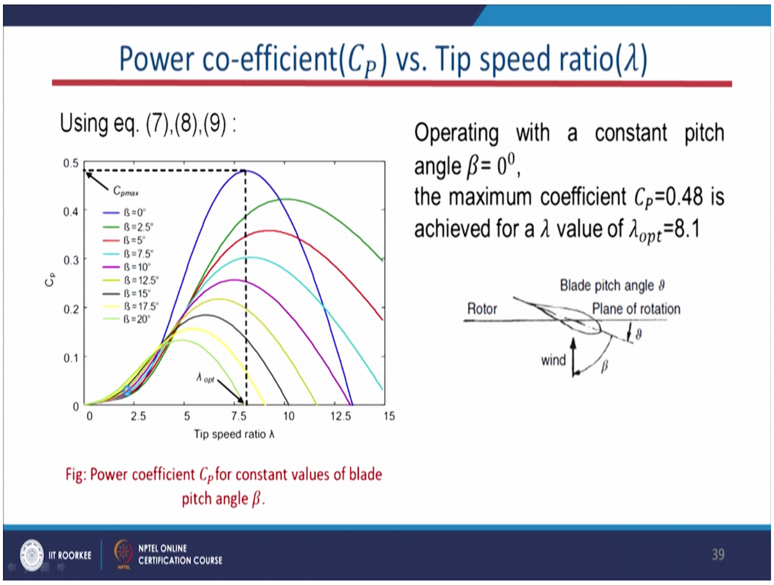

Now, this is the another characteristic which is basically between this power coefficient C P and the tips speed ratio and, here it is by varying this beta already we have discussed this C P equation here, if we could see the C P is dependent on this beta and also the lambda and this ohm. If we vary this beta the pitch angle of the blade, then what will happen the C P will move in this direction. If we keep on increasing so, he say here the blue one is beta equal to 0 degree and here the maximum beta is equal to 20 degree.

So, for beta is equal to 20 degree here is the C P value it is less and, if you just increase I mean this decrease this beta value to 0 degree, then the C P will be maximum. Because why it happens like this if you could see this explanation, I mean this particular equation that beta is in the denominator side. If you increase the beta the C P value will decrease, if you decrease the beta value then C P value increase?

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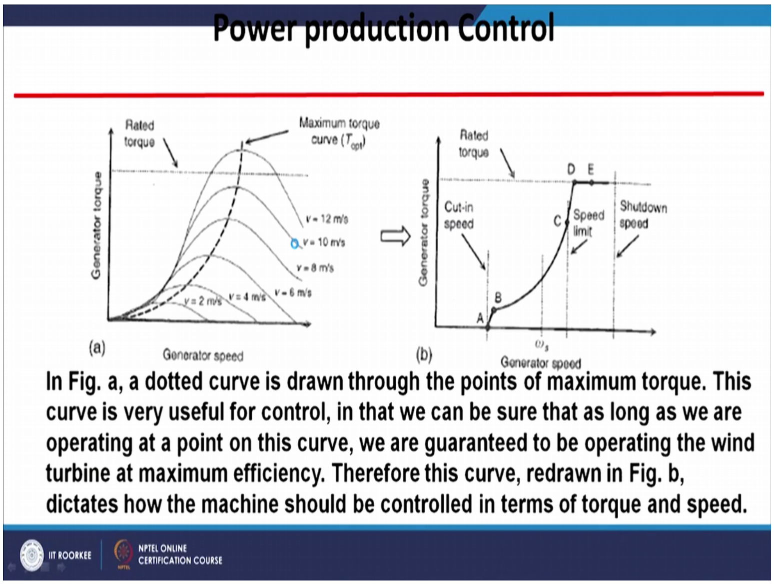

Now, this is the power production curve like for generator side, the this is the generator torque versus the generator speed. So, we have discussed that in this curve the maximum torque point always we have to achieve. Because at the maximum top point we can get maximum output power from the generator, this particular characteristic is where family of curves by varying, this by increasing the wind speed. This is the first curve for when the wind speed is 2 meter per second and, this is for 4 meter per second and so, on. If you increase the wind speed so; obviously, our maximum torque point also will increase and of course, we could not move beyond our rated torque. So, this is here the rated torque.

So that means, this MPPT algorithm helps in achieving this particular maximum torque in the wind system. And these are some of the generator cut in speed and, speed limit and shut down speed. As already we have discussed for the wind system wind turbine system, for the generator also we follow that.

Before I mean below certain speed the generator may not generate, or it may not operate and when it will just cross certain point, then it will this point is known as cut in speed and above that it will just go, and reach the speed limit and this is our rated speed and after certain period it will just go for the shutdown torque or shut down point.

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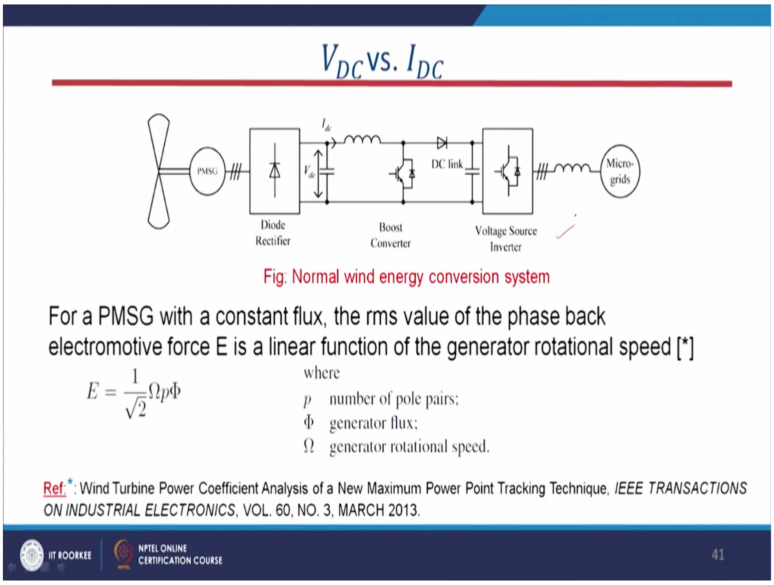

So, just like our wind system this is the one more picture, this I want to discuss that, if you just have a rectifier and invertor system of a permanent magnet synchronous generated type. This is also four type machine basically we also use in the wind system along with the DFIG, doubly fed induction generator. And this machine is also this is not designed for very large scale wind farms, but in large scale wind farm we prefer the variable machines just like DFIG.

And this is also very robust and we also prefer to some extent this PMSG. And these are some of the papers you can follow where every detail, all the mathematical modelling of the invertors convertors are provided and from there actually we have taken this particular picture. And here, I just want to say this V DC versus I DC curve.

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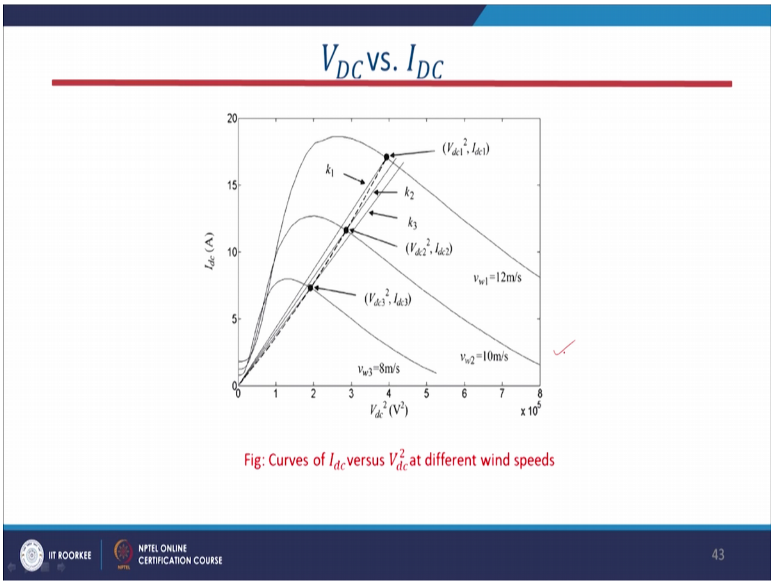

That if you just increase the similar manner for the DFIG, we have discussed if we increase the wind speed, then this I DC is also will increase and, similarly V DC square versus this I DC curve looks like as the similar pattern, we got for the DFIG machine here.

Now, so in this particular wind system, we have discussed about the different operating principle of the wind system it is advantageous it is disadvantageous. And then further we have discussed the constructional features of the wind system and, again we have discussed like fixed mode of generating system. That is the synchronous machine based wind system. And, then we have discussed the doubly fed induction generator where we advantages like, 70 percent of the stator power basically pushed through the line and 30 percent of the power is basically delivered through the powertronic invertor to the grid system. And there we can maintain the frequency of the PCC bus may be voltage also and voltage frequency both together, we can maintain at the fixed value according to our desired requirement.

And further again, we have discussed the wind power content that is our P, which is basically depends on the C P the row and the area of with swept area and also the volume of the wind speed. And finally, also we have discussed different characteristics both for the wind turbine as well as the generators.

Thank you so much.