Renewable Energy Engineering: Solar, Wind and Biomass Energy Systems
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Lecture – 34
Characteristics and Power Generation from Wind Energy - Part I

Hi everyone, today in renewable energy engineering: solar, wind and biomass energy system, we are in last week of this course.

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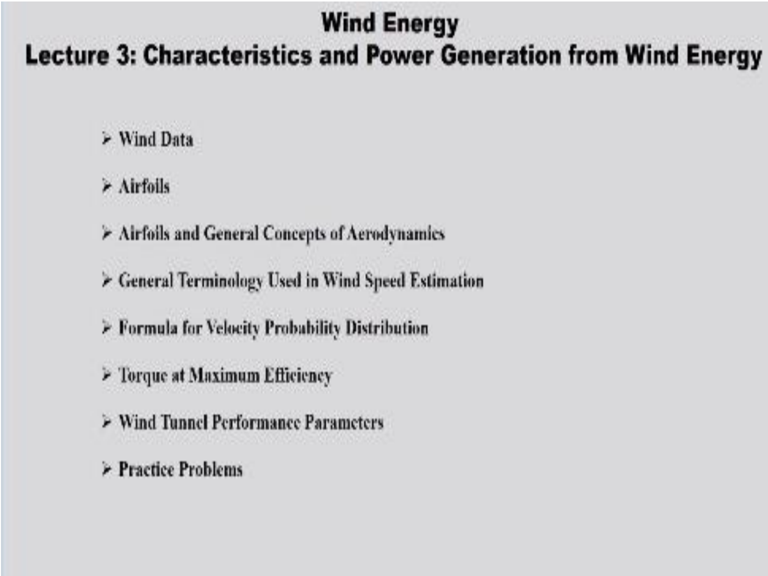

And today, what we are going to see is lecture 3 of wind energy. So, characteristics and power generation from wind energy.

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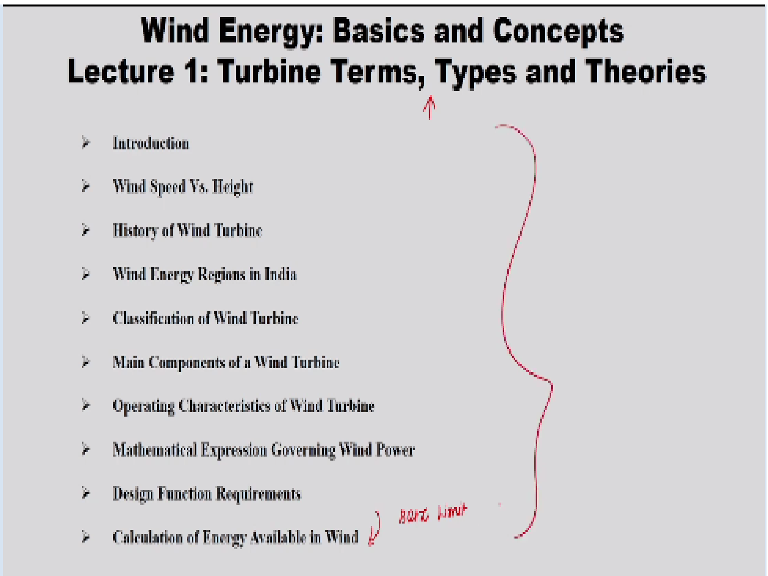

And before that we will review the lecture 1 and 2 whatever we have done in last week. So, we have almost spent 2 lectures on turbine terms, types and theories, because, we calculated the calculation of energy available in the wind. So, that is nothing but, Betz limit to derive that it took almost one lecture. So, we spent in lecture 1 and 2 on turbine terms, types and theories. So, these are the topics we discussed. So, before going into today’s lecture, we will review what we have done last week.

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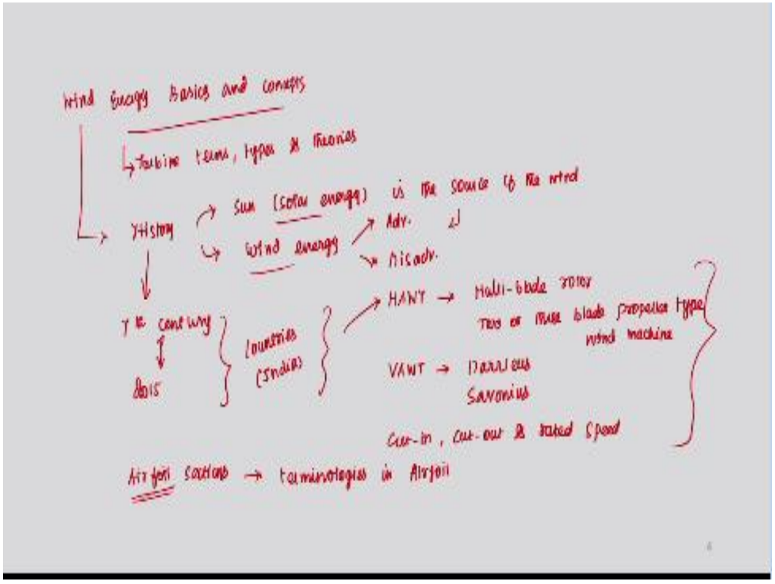

So, basically in wind energy basics and concepts, we reviewed in the last week. So, in that turbine terms, types and theories related to it, not only we straightaway went here. So, first, we had seen about the wind energy. So, the history so, which is nothing but the sun, our solar energy is the source of the wind and wind energy advantages and disadvantages. So, it is almost a similar because both wind energy and solar energy comes under the category of renewable energy and both are intermittent we would not get throughout the year or day.

So, that advantages, disadvantages are there. Advantages abundant in certain locations, we do not need to pay for anything because it is a natural source, but disadvantage site that collection and storage is always there. The next one what we have seen is the history of the wind energy when it started from almost 17th century to till 2015. What happened in the improvement of wind energy harvesting, so, that we had seen and this includes countries as well, so, especially in India also.

So, what are all the possible locations, we have seen in which states the abundant wind energy is available that we have seen. So, while doing this one, we introduced certain terminologies before going into those terminologies, we use the certain things. One is horizontal axis wind turbine. So, in that so, we had also introduced about multi blade rotor system or 2 o 3 blade propeller type wind machine.

And in vertical axis wind turbine, so, we introduced you about the Darieus type and Savonius type. So, apart from these 2, we also introduced about the cut-in speed, cut-out speed, and rated speed. So, when we talk about history itself, we told you about these terminologies. Then after that somewhere, we said that the blade has airfoil sections, because we introduced the terminology airfoil.

So, we have also reviewed about certain terminologies used in airfoil for that aerodynamics concepts or fluid mechanics concepts are required something of this kind.

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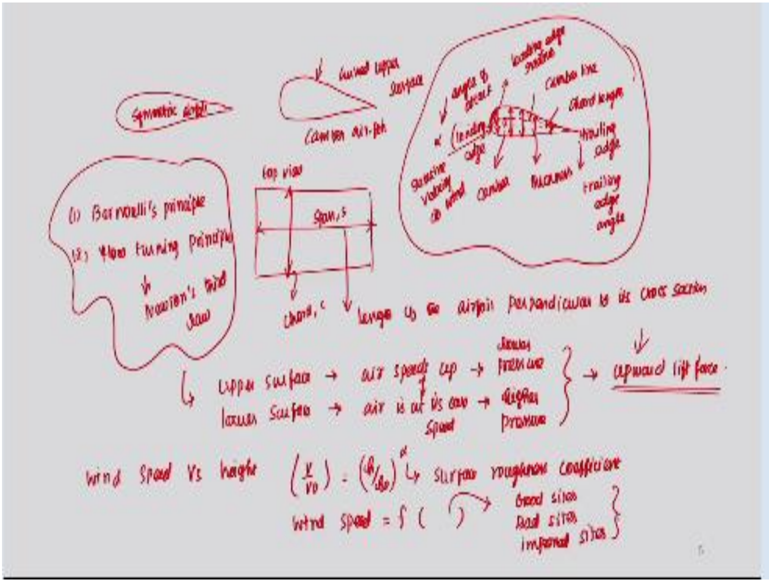

So, this is symmetric airfoil and another one is something like camber airfoil. We did not go in depth, because it has the curved upper surface but still we said certain terminologies in airfoil section. So, what are all those so, that is something called. So, this is leading edge. This is trailing edge. So, the line which connects is called chord length. Then we connected upper surface with lower surface, so, that we call it as a thickness.

So, if you take middle point of thickness line and connect them, so, middle point of thickness and connect them, then you would get camber line. So, the distance between camber line and chord is called camber. Apart from that, so, you may have this particular section. So, if you take that from the chord to that leading edge, so, this radius is called leading edge radius and one more thing we told.

So, this is your chord line and this is your relative velocity vector, relative velocity of wind. So, the angle between these 2, the chord and relative velocity of wind is called angle of attack. Angle of attack, leading edge, trailing edge, camber line, chord length, thickness, camber so, etcetera we introduce and this also can be extended this chord line and your camber line and this also called trailing edge angle.

So, these are all the terminologies, we have seen. Apart from that there is something called a span. What is this span? So, if you see this airfoil in top view, so, this is nothing but chord. So, this length of the airfoil particular to its cross section. So, that is called span. So, this is span. This is denoted as S and chord is denoted as a C. So, these are all the terminologies we had seen. And to analyse this one, how the fluid is flowing?

Fluid here nothing but air, over the airfoil section. So, we used to fluid mechanics principle. One is Bernoalli's principle and another one is flow turning principle so, based on Newton's third law. So, by analysing that we came to know the upper surface of the airfoil, air speeds up and pressure is reduced or you can say, lower pressure. So, in lower surface comparatively air is at its own speed. So, here I am saying, comparatively. So, then it is set higher pressure.

So, due to this pressure difference, there is a upward lift force, this, we have seen and also to have high upward lift force then what are all the factors affecting this lift force that we had seen and one point of time, we also told you if you have positive angle of attack or angle of attack is maximum, then you would get upward lift force, but again that is a theoretical saying, but based on certain parameters, till certain angle of attack only, so, that price would be there.

Then after that there may be a decreasing lift force as well, because it is the function of many parameters. So, that is one such case if you have positive higher angle of attack, then you would have higher lift force because here we are saying superficially things, but we are not going in detail, but if it would have been the separate or exclusive course on wind energy, we would have discussed all these fluid mechanics principle in depth or aerodynamics principles in depth.

So, this is what we have done regarding the airfoil section, because, we said that the blades have airfoil sections to have higher lift force. So, then after doing all these things, then we have seen the wind speed versus height. We said that the simple formula which is nothing but V upon V 0 is nothing but h upon h 0. So, 0 refers to height and reference velocity and power alpha. So, this is nothing but surface roughness coefficient.

So, the values are given and wind speed is also a function of many parameters and here we said, one of the parameters the surface turbine. So, there we had seen about the good sites of the wind energy harvesting then bad sites and the sites which can be improved sites which are now having obstacles, but it can be improved as a better sites. So, that we had seen. So, what are all the examples, the sites how it affects the wind energy harvesting.

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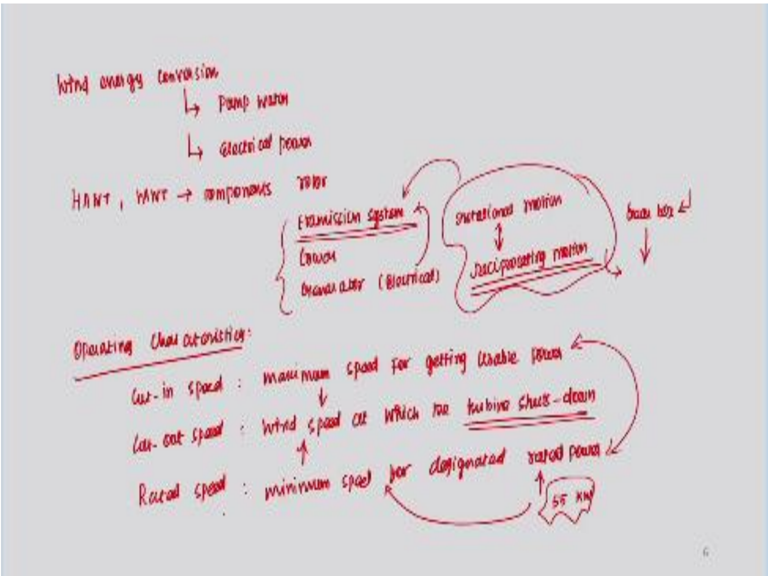

And then we had seen about wind energy conversions. So, as for this course is concerned then we had seen; one is to use wind energy to pump water and to convert electrical power. So, in that line we had seen horizontal axis wind turbine because here we introduced the terminologies, but we had seen in detail horizontal axis wind turbine and vertical axis wind turbine and their components.

So, the main components were rotor, transmission system, then tower and then generator. So, the generator exclusively for electrical energy conversion. So, if you want to have this pumping the water, then you might be having pump. Based on that there is certain components change in transmission system as well. So, if you have here normally you will have low speed shaft, high speed shaft and brake, such things for normal electrical conversion to generate the electricity.

If the wind energy is used for pumping the water, then you might be converting the rotational movement or rotational motion into reciprocating motion. So, if you are using the reciprocating pump or if you are using centrifugal pump, then direct rotational motion can be used. So, regarding this, so, if there is any conversion like this, then you might have such components in the transmission system. One is like a gearbox.

So, in the electrical conversion system then you might have to increase the speed. So, far that gearbox can be used. But if you are using the pumping the water, then this gearbox can be used for some other purpose. So, like this, so, based on your end purpose, there would be components in the transmission system totally in horizontal axis wind turbine or vertical axis wind turbine. So, you might be having the required components based on your end use.

So, that we had seen and then we had seen about the operating characteristics. So, in that cut-in speed so, which is nothing but maximum speed for getting useable power. So, that means what, so, below which you would not get any useful conversion of wind energy and then cut out speed. So, this is nothing but wind speed at which the turbine shuts down. So, that means, the wind speed is so high, your wind turbine will not be able to handle such speeds.

So, in that case to avoid the damage, the wind turbine has to shut down and then rated speed. So, this is the speed. This is the minimum speed for designated rated power if the wind turbine is designed for example, 55 kilowatt. So, for 55 kilowatt rated power and what should be the minimum wind speed you need to have. So, that is nothing but a rated speed. So, normally based on the wind speed, so, the wind turbine operates between cut-in speed and rated speed.

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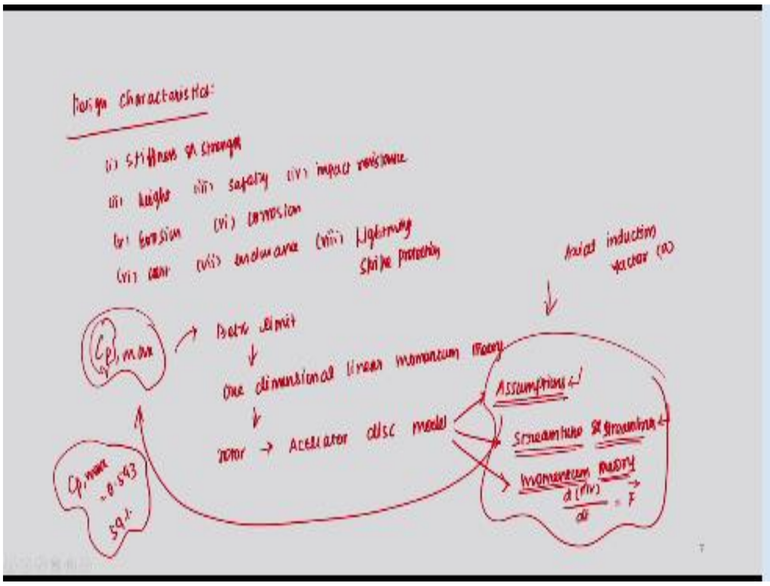

And then we have also seen certain design characteristics. So, that is related to wind turbine blades stiffness and strength. So, second one is weight. Next one is safety. Next one is impact resistance. Next one is erosion; corrosion; cost endurance and lightning strike protection. So, these are all design characteristics we have seen and these are all operating characteristics.

While discussing operating characteristics, the one thing is what should be the theoretical maximum power I will be able to harvest from wind energy for any purpose; for any end use. So, that is what we had to do for that there is something called Betz limit. So, here to derive the C P maximum or this we call it as a power coefficient C P max is maximum power coefficient. C P is nothing but power coefficient. So, we used the one dimensional linear momentum theory.

So, here what he did is, he compared the rotor, is the actuator disc model. So, here, wherever certain assumptions used so, under this assumptions only that C P max of 0.593 or 59% theoretical efficiency would be possible. So, there are certain assumptions and also it is considered as a stream tube and streamlines were used to draw certain principles and apart from that you also should be comfortable with momentum theory.

The basic phenomena would be Newton's second law of motion that is rate of change of momentum. So, momentum is m into V, mass and velocity upon dt which is nothing but the sum of the force applied. So, you should be comfortable with those assumptions used to derive C P is C P max of 0.593 and you should also be comfortable that streamline, stream tube concept and you should also be comfortable with momentum theory and by using these concepts by introducing one more terminology called axial induction factor a.

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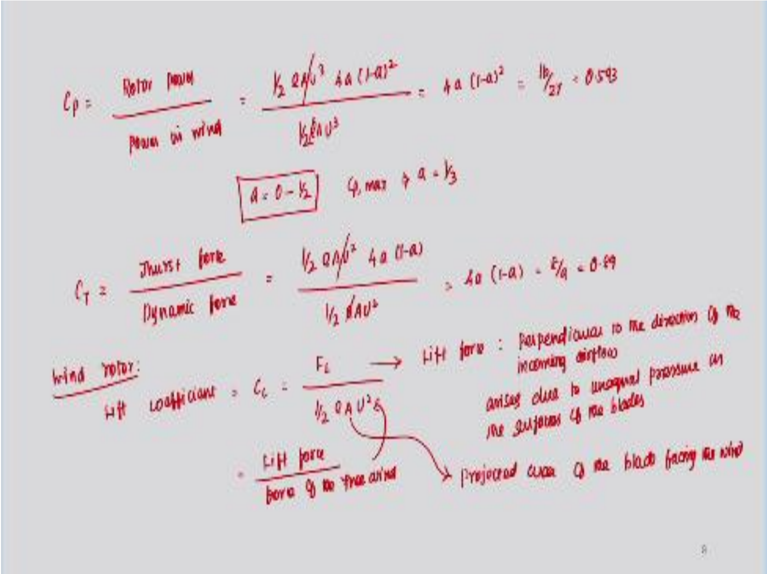

So, we derived certain things. One is C P which is nothing but rotor power upon power in wind. So, the rotor power what we derived is half rho a V q cube. This V, u, I may use interchangeably both are similar; so, this is nothing but free-stream velocity; area is nothing area of the rotor; into 4 a (1 – a) whole square upon the power in wind also we derived, 1 upon 2 rho a u cube. So, what you would get is 4 a (1 – a) square.

So, we said that to get maximum power; a should vary to get a C P; a should vary between zero to half. So, in that to get maximum power that is C P max, so, a should be 1 upon 3. So, if you substitute here, so what you would get is 16 upon 27 which is nothing but 0.593. Then we also derive thrust coefficients C T. So, which is nothing but thrust force upon dynamic force which is nothing but half rho A u square 4 a into (1 – a) upon half rho A u square.

This gets cancel. It became 4 a into (1 – a). So, this become 8 upon 9 that is 0.89 and also we had seen related to wind rotor. There are certain other coefficients. So, one is lift coefficient. The first one is lift coefficient which is called C L which is nothing but F L upon half rho A u square. So, what is this F L? F L is nothing but lift force so, which is perpendicular to the direction of the incoming air flow.

And it may arises due to unequal pressure on the surfaces of the blades. So, this we had told in airfoil section itself. So, this also can be defined as lift force upon force of the free wind.

So, this total terms is force of the free wind. So, what is this area? So, this u is free string velocity; area is nothing but a projected area of the blade facing the wind.

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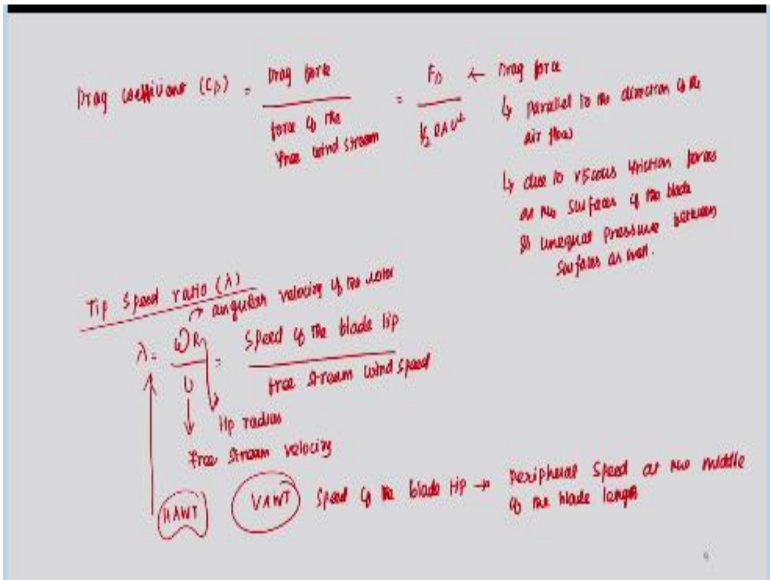

So, then next one is drag coefficient so, which is nothing but C D, so, which can be defined as drag force upon force of the free wind stream. This can be written as F D upon half rho a u square. So, what is F D? F D is drag force. So, this is in direction wise parallel to the direction of the flow and this may arises due to viscous friction forces at the surfaces of the blade and due to an equal pressure between surfaces as well. So, this area is same.

So, now, we had seen lift coefficient and then drag coefficient. So, another terminology is tip speed ratio so, which is defined by the symbol lambda. So, lambda is nothing but omega R upon u. So, what is omega R? Omega R is nothing but speed of the blade tip upon u is nothing but free-stream wind speed. So, what is omega? Omega is nothing but angular velocity of the rotor. What is R? R is nothing but radius.

So, what is u? u is nothing but free-stream velocity and then remember so, this should be used for only horizontal axis wind turbine. So, if you had to use vertical axis wind turbine so, then how to calculate speed of the blade tip because, we already said vertical axis wind turbine the wind direction is different. So, this speed of the blade tip can be replaced by peripheral speed at the middle of the blade length.

So, that one should remember. So, other things you can use irrespective of the type of wind turbine, but here when you define tip speed ratio as well as solidity, then you need to remember which kind of wind machine you are supposed to calculate tip speed ratio and solidity. So, what is solidity?

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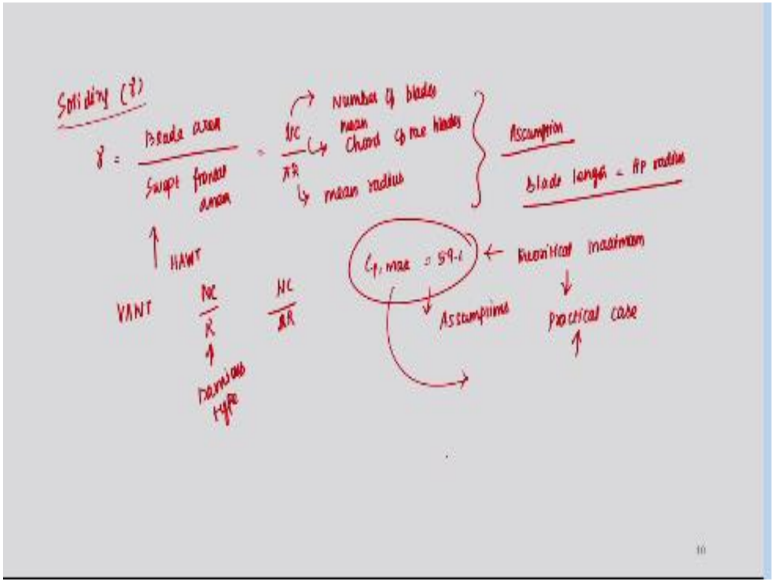

Solidity is defined as gamma. So, gamma is nothing but blade area upon swept frontal area. So, this is defined as N C upon phi R. So, what is N? N is number of blades. What is C? C is nothing but chord length or mean chord of the blades and then R is nothing but mean radius. Remember, here also the assumption is, blade length is equal to tip radius. And also this is used for horizontal axis wind turbine.

As I said earlier if it is a vertical axis wind turbine, then you supposed to be using N C upon R for various type wind machine. For other vertical axis wind machine, we supposed to use N C upon 2R. So, we have not discussed how we arrived at such formulas. So, here we are defining it as a formula to calculate solidity tip speed ratio etcetera. So, this is about all these coefficients. So, then apart from this, we had also seen the C P max as 59%.

So, for that we used certain assumptions and also we call it this as a theoretical maximum. So, but this is the ideal case, but what happens when we go to the practical case. Practical cases in the sense, when we really employ the wind turbine, so, out of this theoretical maximum, how much we will be able to get, but that losses, what are all those losses due to which out of this 59% of theoretical maximum, how much we will be able to get.

So, from then onwards, we are going to discuss in today’s lecture. Apart from that we will also see how to represent the wind data and how to collect the wind data and how to calculate the wind speed and what are all the statistical models available etcetera that we are going to continue.

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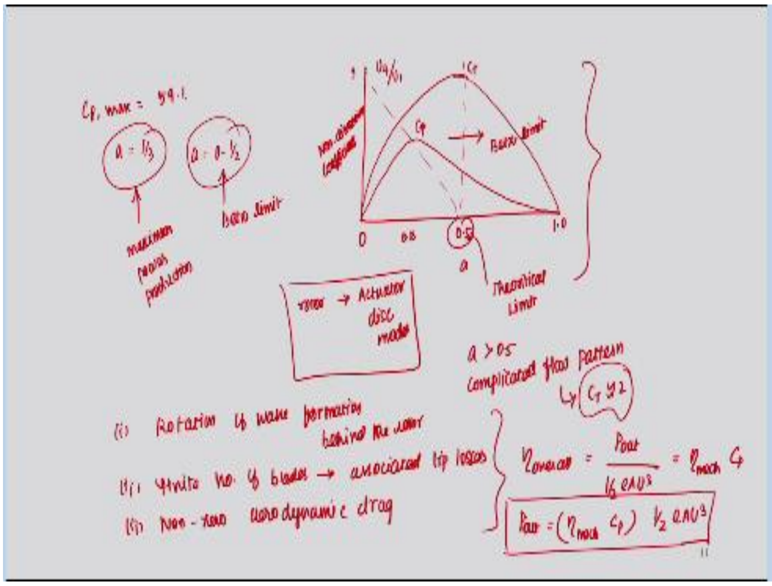

So, if you remember, for to get C P max of 59%, we used the induction factor, axial induction factor, so, that should be 1 by 3, but the minimum maximum limits we calculated were 0 to 1 by 2. So, this we call it as a Betz limit. So, this we call it as the maximum power production happens. So, if we draw graph, so, a ((()) (36:13) 0 to 1. This is 0.5. This is nothing but betz limit only it can vary 0 to 0.5 but our maximum C P happens at around 1 by 3. 1 by 3 is nothing but 0.33.

So, that is where your maximum C T happens. So, this we call it as a non-dimensional coefficients. So, if you draw that u 4, u 4 is nothing but your downstream velocity; u n is nothing but your upstream velocity. So, that is maximum when axial induction factor is 0 that is 1. So, it reduces to 0.5. So, this is C P. So, maximum power coefficient happens when a equal to 1 upon 3 and C T is, so, we got something around 0.89.

So, this is maximum C T 0.89 and it decreases after that. So, this particular line, we call it as Betz limit. This is a theoretical limit but maximum happens at 0.33. So, this is the theoretical limit, one can vary a between 0 to 0.5. So, then we might be having. So, this is the theoretical maximum. So, is that something we need to fix a as 0.5 or we can go beyond that.

So, remember he considered and compared the rotor with the actuator disc model, so, that is nothing but simple model so, which has this constraint due to assumptions made. So, otherwise in practice, your a can go beyond 0.5 and accordingly there may be a complicated flow patterns arises because you cannot analyse when a goes greater than 0.5. You cannot analyse the wind turbine using the actuator disc model.

So, in that case, there would be complicated flow pattern. So, that rise to even C T of approximately 2, but here it is not 10. It is 1.0 that is one. This non-dimensional coefficients also 0 to 1. So, it may go to C T of 2. So, what are the reasons for that? So, the reason is, there would be a rotation of wake formation behind the rotor. So, the second reason would be finite number of blades because we consider infinite number of blades.

So, if you consider this, then this lead to associated tip losses. The another reason would be non-zero arrow dynamic drag. So, due to these reasons, so, where we considered no way formation, no drag forces and infinite number of blades as assumptions. So, because that is not possible in the practical cases then this will not be applicable. This theoretical limit you will not get in practice.

Apart from that you will have the normal losses due to transmission system etcetera also when you are harvesting the useful power from wind energy. So, because of which the overall efficiency of the wind energy conversion would be defined as P out, output power upon the what one that actual power wind has rho a u cube which is equivalent to the n mechanical efficiency into C P. CP is nothing but power coefficient how much power you are getting that is multiplied with mechanical efficiency.

So, if you want to calculate power output, so, then that is nothing but mechanical efficiency of the system and power coefficient which is multiplied by half rho a u cube. So, this is the way you calculate output power or if you are given output power, then this is the way you calculate overall efficiency using power coefficient and mechanical efficiency is given. So, this is all about what we have discussed in past 2 classes.

And here, we used the linear momentum theory to derive this power coefficient. So, this also can be done with certain correlations.

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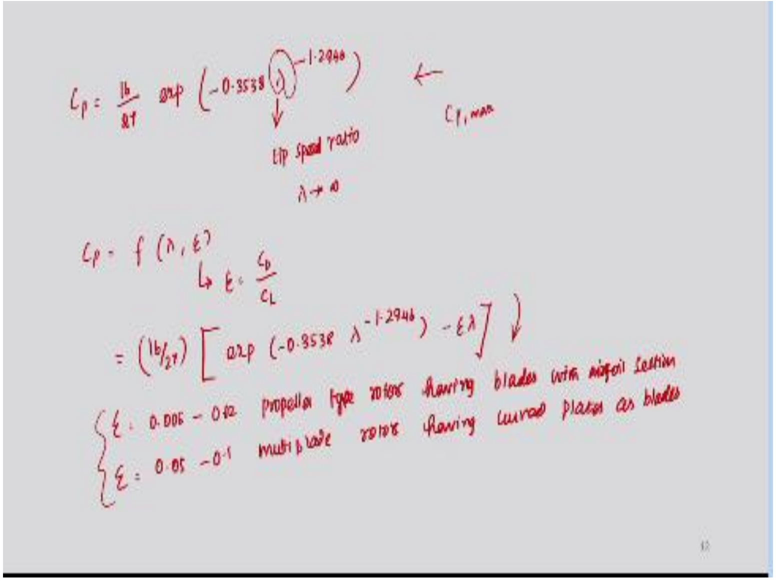

So, one such correlation we would be seeing now, so, that is nothing but C P is 16 upon 27 exponential minus 0.3538 lambda power minus 1.2946. So, what is lambda here? Lambda is whatever we defined here which is nothing but tip speed ratio. Power coefficient can be defined as a function of tip speed ratio as well. So, you know, when lambda tends to infinity, then you might get the maximum power production of 16 upon 27. This C P also can be expressed in terms of lambda which is nothing but tip speed ratio and epsilon.

So, epsilon is again defined as C D upon C L. What is C D? C D is drag coefficient. C L is lift coefficient. So, for that the formula would be 16 upon 27 exponential minus 0.3538 lambda into lambda power 1.2946 minus epsilon lambda. Epsilon is defined here and this epsilon also varies based on the type of the rotor we use. So, this varies between 0.008 to 0.02 for propeller type rotors and rotors having blades with airfoil section.

So, it varies between 0.05 to 0.1 for multi-blade rotors having curved plates blades. There might be certain values this I have given as example, so, you can refer Professor Sukhatme solar energy book to get to know end up about this and also you can vary the lamda and see where you get C P max and you can also explore about the epsilon which is nothing but C D upon C L.

You calculate and try to get what is the C P as a function of lambda and epsilon. So, I already told, I am not very fond of explaining you the graph that is decreasing increasing. So, you were given the formula and required concepts so, that you can substitute and play around and try to check how C P is dependent on lambda as well as epsilon. So, that is all about the basic turbine terms, theories, types and then also we had discussed about certain coefficients; power coefficients, lift coefficient, drag coefficient, tip speed ratio and then solidity.

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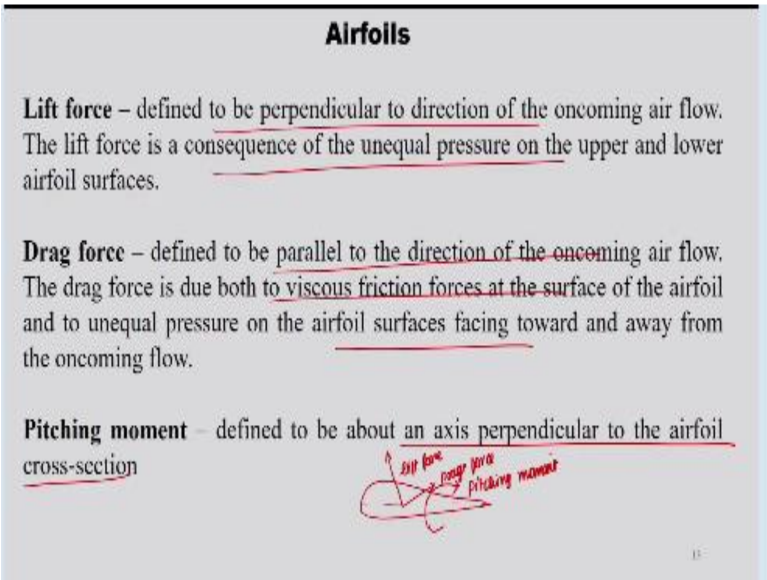

So, now, we will slowly see certain definitions, this I already had told you, when I was explaining lift coefficient, what is lift force. Drag force also I defined when I was explaining drag coefficient and what is this pitching moment? Pitching momentum is defined to be about an axis perpendicular to the airfoil section. So, if you are taking airfoil section, so, this is your lift force. This must be your drag force.

So, what is pitching moment? Pitching moment is nothing but axis perpendicular to the airfoil cross section. So, it is something about this side. So, that is pitching. So, this definition we already had seen first or second lectures and then the airfoils and certain concepts of aerodynamics.

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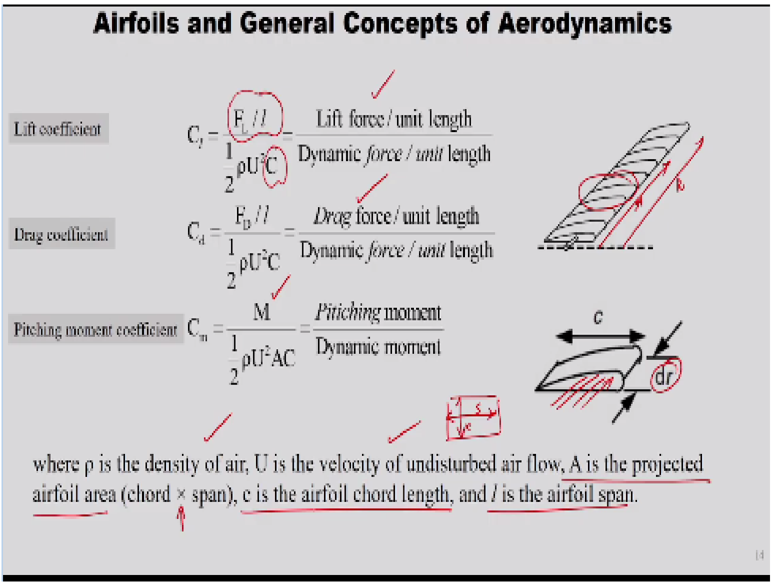

So, if you want to define in terms of airfoil. Whatever we have done here, it is based on the blades whatever we defined the lift coefficient, drag coefficient etcetera. So, if you want to define in terms of airfoil section that also can be done. So, C L is nothing but lift force upon unit length divided by dynamic force upon unit length. So, here the A is replaced with c. c is nothing but airfoil chord length. L is nothing but airfoil span.

Span also I defined you what is span in the airfoil terminology and drag coefficient is F D upon L which is nothing but drag force upon unit length divided by rho u square C again c is nothing but airfoil chord length and pitching moment coefficient is nothing but pitching moment capital M upon half rho U square AC. What is A? A is nothing but projected airfoil area which is equal to chord into span.

If you remember that top view when we talk about top view of the airfoil, so, this is nothing but your chord; this is nothing but your span S and C. So, that is nothing but A is the projected airfoil area. So, in terms of airfoil also, you can define all this coefficient; lift coefficient, drag coefficient and pitching moment coefficient. And now, you might be like, we were talking about the airfoil, airfoil where is that I mean, how it looks like.

So, if this is the blade if you cut into different for example, so this is the r direction, so, this is the total capital R. So, if you take one particular section and cut it, so this is the way it looks like. So, this section is nothing but dr. So, this is nothing but chord length. So, this is the way it looks like. So, this is what we are telling that as a airfoil and we discussed about certain general concepts of aerodynamics with respect to airfoil.

And here rho is the density of air, U is the velocity of undisturbed air flow or you can define it as a free-stream velocity. A is the projected airfoil area, because we use to capital C, here also should be capital C is the airfoil chord length. L is nothing but airfoil span.

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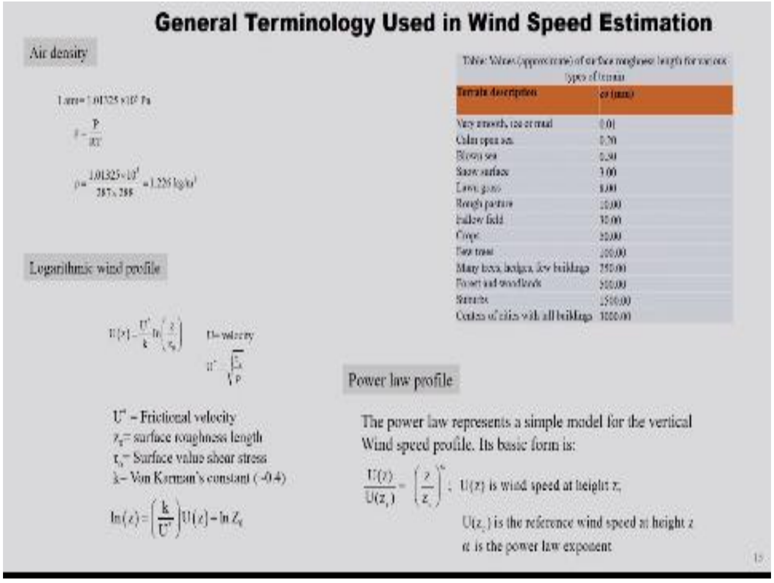

And now, we are slowly moving into what are the general terminology used in wind speed estimation. Before going into that we will see how one would get the wind data.

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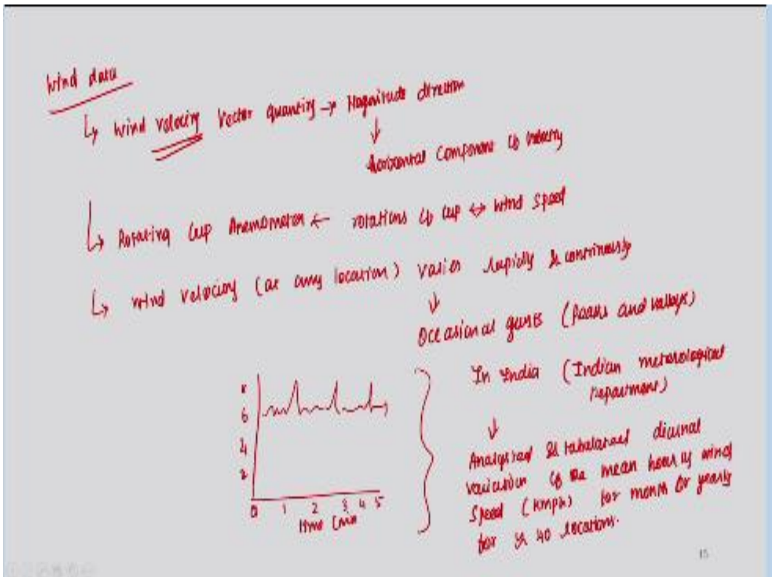

So, to get wind data, so, we already know the wind velocity or not wind velocity, so, any velocity. The velocity term itself is nothing but a vector, vector quantity. So, this has magnitude as well as direction. So, magnitude wise you have, for example, if you are taking 2 dimensional x and y, both horizontal and vertical component would be there, but because of the things what we use in wind energy conversion, since we are using horizontal axis or vertical axis wind turbine.

So, to convert the wind energy into useful form, we here only take the horizontal component of the velocity. The equipment used is the rotating cup anemometer. So, this we know that this is the experimental measurement. So, here the rotations of the cup is calibrated with this wind speed, so, that is the way you could get wind speed based on the rotation of the cup.

And the wind velocity at any location varies rapidly as well as continuously and also if you see the wind data, you would get occasional gusts as well. So, due to which you would get peaks and valleys. So, if you see the wind data, so, this is time probably minutes. If we take so, 0, 1, 2, 3, 4, 5. So, wind velocity is 2, 4, 6, 8. So, any at one particular time, what do you get is something of this kind. So, then how to get this data or reasonable data or what we can analyse.

So, in India, so, such kind of data would be provided by IMD, Indian Metrological Department. So, this can be further analysed and tabulated as the diurnal variation of the mean hourly wind speed that is in kilo metres per hour for monthly data or you can get year also or yearly. For about 40 locations, we have but we will also see how it can be obtained for any new locations.

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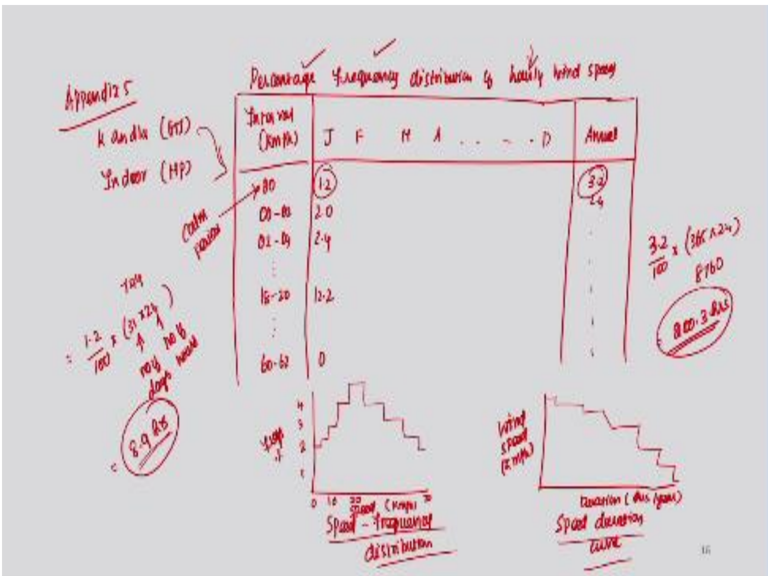

So, if you go to Professor Sukhatme’s book in appendix file, it is tabulated for 2 cities, one is Kandla in Gujarat and second one is Indoor in Madhya Pradesh. So, how it was tabulated? It was tabulated as percentage frequency distribution of hourly wind speed. So, this is nothing but the interval which is in kilo metres per hour. For example 00, 00 to 02, 02 to 04 then 18 to 20, so, like that till 60 to 62, 2 kilometres per hour interval.

And you would get in throughout the year January, February, March, April then till December and you would also get annual. It is how much. So, for example, for January 1.2, 0 kilometres per hour; 0 to 2 then you probably getting 2; then 2 to 4, 2.4; then 18 to 20, 12.2; and 60 to 62 that is almost 0. So, annual also, it is given. For example, this 3.2, then 2.4, then etcetera, etcetera so, you would get. So, this kind of table is given for both the places.

So, you can refer to that. So, here if you want to calculate for example, what is this? This is a percentage frequency distribution. So, if you want to calculate how many hours you are getting, so, for example, in January, it is 1.2%, so, 1.2 upon 100 into number of days, remember it is number of days into hour, hourly wind speed, so, 31st into 24 hours. So, this is number of days; this is number of hours. So, it is coming as 744.

So, what do you get is around 8.9 hours. So, if you want to calculate for annual one, so, then you supposed to do 3.2, 3.2 is 3.2 upon 100 into so, 365 days hope it is a non-leap year, so, 365 days into 24 hours. So, this would be coming around 8760. So, the number of hours would be 280.3 hours that is the way you can calculate for zero kilometre per hour. So, this we call it as calm period where there is no wind.

So, in January month, for this place Kandla in Gujarat, so, you would get 8.9 hours in January and the same is around 280 hours in annually. So, this data, one can get and also if you want to how do I represent in terms of graph, then there are 2 methods. One is speed frequency distribution and second one is speed duration curve. So, in both cases, the frequency percentage, not both cases in speed frequency distribution, frequency percentages in y axis; in speed duration curve, wind speed is in y axis which is nothing but kilometre per hour.

So, x axis in speed frequency curve is speed which is nothing but kmph. So, this is we already told it, so 0, then 10, 20 till you can have 60 or 70 and here you know for zero then it is around 1.2. So, this if you take it 1, 2, 3, 4, etcetera, so, it is around 1.2, o to 2 then you supposed to see 2 to 4, it is zero it is 1.2 and zero to 2, it is around 2% to 2%. So, then 2 to 4, it is around 2.4%. So, like this you can go about.

So, this graphs something goes like this or you can do it with duration, this is wind speed versus duration. Duration is nothing but days or hours because it is hourly distribution, hours per year. So, you know, how to calculate these hours. So, what is the wind speed you know, so, then from that you can plot this graph. These all things you can get it from Professor Sukhatme's book as well.

So, 2 types you can do or you can tabulate as well. So, then there comes a question like how do I do it for new location? Because, it requires extensive measurement as I might have told you in one of the lectures that these are all like naturally available energy, it cannot follow same pattern. So, now, also you are experiencing, but this time when you are watching this lecture, you know what is happening parallely in Texas.

So, if you see whether the same thing happened last year, probably not. So, every year we are contributing also the negative side for the environment. So, because of which the things are changing, due to which you need to have these experimental measurements over the years, then only you can clearly say how much is the frequency distribution. So, because of which all these models would be statistical models, because you need to also introduce the probability factor. So, how much it can happen.

So, because of which we use certain statistical models instead of directly going for experimental measurements from which we get the graph using these experimental measures, there are models with which one can calculate this wind speed. So, that is what we are going to see.

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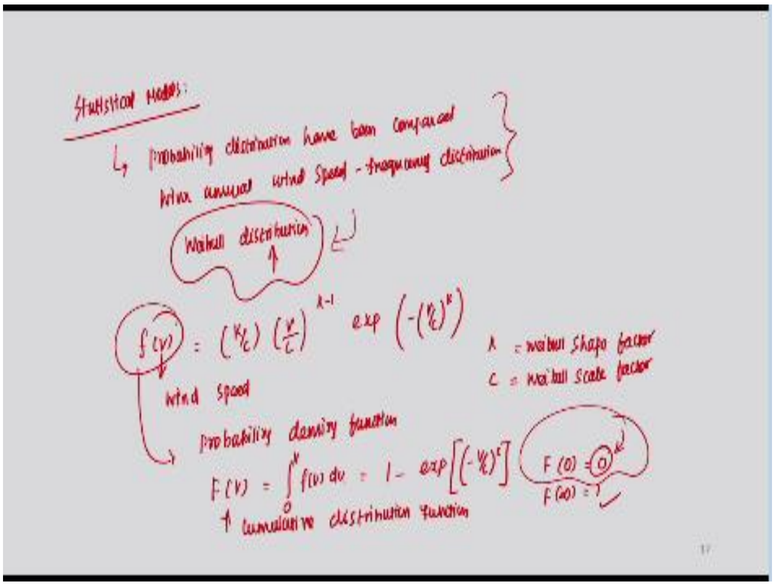

So, these are nothing but statistical models. So, this as I said earlier, these statistical models or probability distribution have been compared with annual wind speed frequency distribution. So, based on this comparison, so, it looks like Weibull model or Weibull distribution is giving near accurate results between the experimental measurement and the statistical models.

So, that we are going to see, so, what is that? That is nothing but f V which is equivalent to k upon c V upon c power k – 1 exponential minus V upon c to the power k. So, what is this V? V is nothing but here wind speed. So, what is this total f of V? f of V is nothing but probability density function. What is this k and c? k is nothing but the Weibull shape factor; c is nothing but the Weibull scale factor.

So, there is something called capital F of V which we call it as cumulative distribution function. This, we take it as 0 to V, f V dV, it is integrated over 0 to V velocity which is nothing but 1 minus exponential of minus V upon c to the power k. So, if you substitute here in the cumulative function when velocity is 0, when V equal to 0, so, this is 0. Exponential e power 0 is 1. So, 1 – 1 is 0 and if you substitute V as 1 or V as infinity, so, then exponential to the power minus infinity is 0 and what do you get this 1.

So, this seems to be but when you are seeing velocity equal to 0, what you are getting cumulative distribution function is 0, but that was not the case when experimental measurements were being made. If you see still 8.9 hours of calm period we are getting, so, due to which this model may deviate from the experimental measurements near to calm period or 0 wind speed period.

But otherwise seems to be a near accurate statistical model in terms of experimental measurements, because these were tested against many experimental measurements. So, seems to be a working model.

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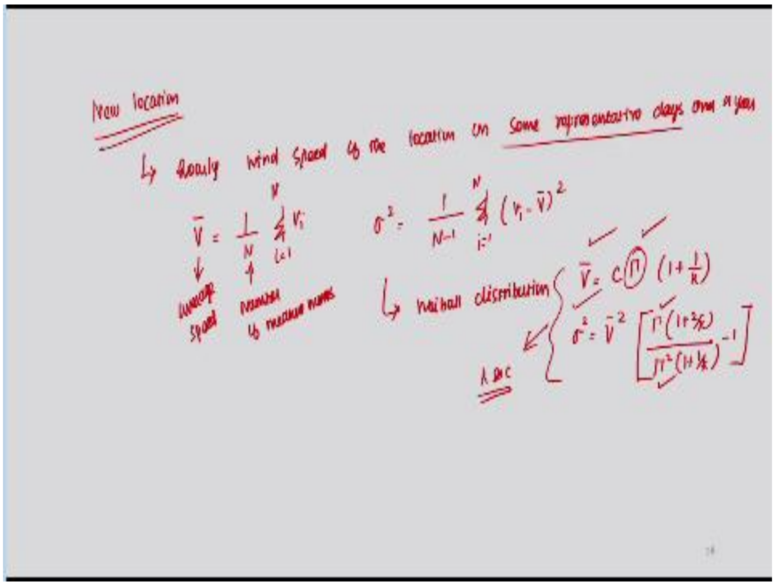

Now, the question is how do I do it for new location? So, this we explained when we were having lecture on solar energy as well. So, either I will be comparing the same location, so, near about that there is some limit for example, it should be within 0 to 120 kilometre. Within which if 2 locations are there, if one location already I have a data, then other location can also use the same similar data that is one possibility.

Other possibilities do proper experimental measurements or do it statistical models or using correlation one can do it. So, here to have it in new location, then you can measure the hourly wind speed of the location on some representative days over a period. So, remember some representative days, then you find out average velocity which is nothing but 1 upon N. So, N is nothing but here number of measurements.

Then summation of i is equal to 1 to N V l. So, after doing that, so, what is this? This is average speed, average velocity or average speed and then you calculate standard deviation. The formula is sigma square equal to 1 upon N – 1, then you calculate i equal to 1 to N the deviation. So, what is that particular location deviates from the average one. Then after calculating this, then you go back to Weibull distribution which is nothing but V bar nothing but C gamma 1 + 1 upon k, k and C are Weibull constant shape factor and scale factor.

Then sigma square is average velocity is defined here as a function of C and k and there is a function called gamma function that I will tell what is that. So, V bar square into gamma 1 + 2 upon k upon gamma square 1 + 1 upon k - 1. So, here also, the function gamma is being used. So, this is a gamma function you can get it from any standard mathematics book Kreyszig. So, these 2 equation, Kreyszig is one of the Applied Mathematics book, you can get this gamma function.

So, these both equations had to be solved simultaneously to get k and C. If you fix the gamma function, you know average velocity and standard deviation then you can fix k and C values. So, once you fix k and C then you are supposed to calculate the probability density function using k and C values and this V is nothing but for example, if you have 0 to 2 kilometre per hour, so, the average middle point is 1.

If you substitute 1, then you would get wind speed for that, so, like that you can generate the speed versus frequency distribution curve or tables.

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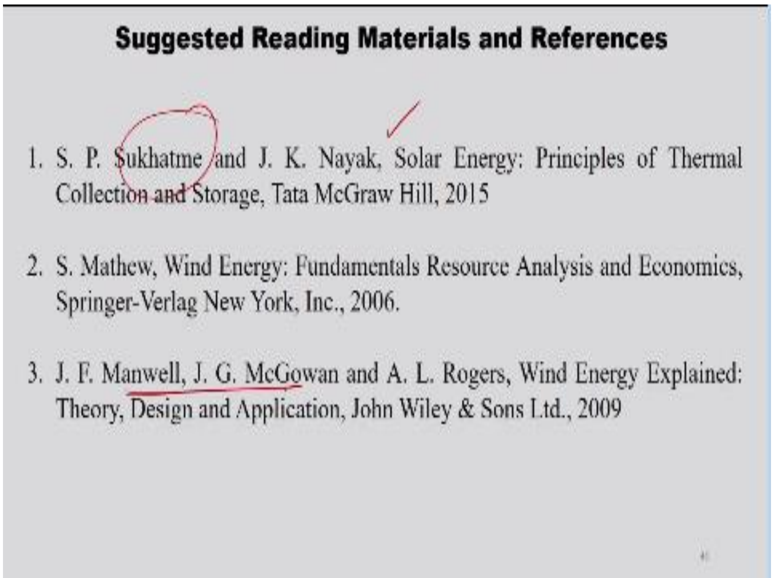

So, whatever we discussed today, so, you can refer these books of solar energy principles of thermal collection and storage by Sukhatme and Nayak and fundamentals of resource analysis and economics by S Matthew on wind energy and then wind energy explained theory design and applications by Manwell and McGowan, Rogers. These statistical models and related concepts were taken from this reference.

The Betz limit and one dimensional momentum theory were taken from Manwell. This also was referred for certain basic concepts. Thank you.