Wind Energy

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Lecture 13: Mechanics of Wind

Welcome back to our continued discussion on the different wind turbine technology. So, now what we can talk about the finally look at the some of the transmission basics and the cost calculations and all this. So, that kind of concludes the discussion on different topics and all these things. So, now what we continue here is that improving the system stability through addition of wind turbines. What has been thought of until now that wind turbines have been the only liability as far as system stability is concerned, because mostly due to the fluctuating and partly uncritical nature of wind, which is the biggest concern. The reason is that we have seen the variability in wind speed, the fluctuations and all these things.

Obviously, modern wind turbines can be used to improve the overall system stability by compensating for shifts in reactive power related to phase shift between voltage and current fluctuations or oscillations caused by other supply sources and all this. maintaining the connection to the grid and continuing production, varying their output in response to changes in the grid frequency. All this one can adopt and then you can improve the system stability. So, obviously how your natural process reacts you can actually change in your operational parameters or design parameters or maybe the other constants so that you can improve the system stability.

So, overall idea here is that to have an improved system stability, which can provide to sustain wind energy productions and things like that. some basics on the transmission because obviously we know one hand there are production then production is not all you can have some basics on transmission like the transmitted power is the voltage into current, obviously the loss varies with l square, i mean, for given energy flow the resistance loss varies with one by v square So, we need to minimize the resistance losses in transmitting electricity at high voltage. That means, if you have long cables, then the losses will be more. Obviously, some offsetting losses are there. Typical long distance transmissions are compared to 30 kilovolt for local distribution.

One important aspect is that where your farm is located so that you transmit the electricity to the grid. So, if you can have to transmit lesser distance, then you can minimize the losses. So, what I mean, when you talk about that, then obviously you can think about that this particular subject is such a multidisciplinary subject. Because one has to not only understand the fluid mechanics or aerodynamics of the turbine, you need to understand the structural mechanics as well because, you have to have some base or foundation, design of towers and, the mechanical aspects of it, then the electrical aspect of it. Because you can generate the electric power, but then transmission, there will be losses.

Then how you connect with the grid, then how you convert the AC to DC or DC to AC conversion. So, all these processes, whenever there will be some kind of losses associated with that. So, any loss that you have in the system, that's going to finally affect your overall output of the power production and obviously, if there are some impact on the power productions you are going to have some impact on the cost and other things what also one has to understand a bit is that high voltage DC so less expensive transmission lies with smaller resistance losses but more expensive transformer with greater losses. So, if your wind turbine produces AC electricity as it's popular in the DFIG type of generator, then we need to convert from AC to DC with a transformer. Obviously, this would have some energy loss.

Transmit as DC and then convert back to AC. That means my turbine is producing AC. Then, I have to convert that to DC for transmission purposes because all the transmissions are directed voltage direct current and then again I have to convert back to AC for regular use or common use so this conversion process will definitely add to some of the losses that you encounter and any loss as I have said it is going to hit your overall However, if you have a high voltage DC cost less and intense less overall loss of transmission beyond some minimum distance, let's say some distance beyond 750 kilometer distance, it will intense less beyond about 50 kilometer distance, obviously. But, the catch here is that your turbine has to produce. Basically, the DC as the first step, which is that use the generator like PMSG, i.e, permanent magnet synchronous generator. PMSG is the permanent magnet synchronous generator. So, those kind of generators, if you use, then it can produce directly DC. Then we can save on DC to AC conversion. So, your turbine directly produces DC.

Then you transmit that. Then only one conversion DC to AC. Then directly use. so, you can avoid the need for those transformer and then before high voltage dc transmission and losses so idea here is that as long as you avoid any of these conversion processes or as you can minimize these conversion processes ac to dc dc to ac and whatever it is then you can definitely improve your overall performance output and it would lead to cost as we can see that one can calculate some of these direct cost of the wind energy which is have this is cost recovery factor which has been given the interest rate number of years and annual operations and all this when is the annual operation maintenance cost initial capital cost then your efficiency, some fraction of available time, then capacity factor. So, you can see here, this is an efficiency that takes into account variable losses that are out of account in the turbine power curves, such as cut on the blades, imperfect tracking of the wind directions, your mechanism, weak effects in wind turbines, fa is the fraction of the time that your turbine is available for you, so obviously, that also taking into account then capacity factor that is the average power output is a fraction of the peak power output of the capacity and then kilowatt turbine running for long top so you can have this cost calculations in that way and that gives you kilo or some dollar per kilowatt or if it is in other currency something like that so this cost calculations would have, so that means, overall, as i mean, the idea would be to reduce your losses as much as possible availability of the turbine for you should be as higher as possible and other things if you minimize then this is some initiative illustrative cost of wind electricity or various rates of return based on i mean over here for a capacity factor of 0.

$$C = (CRF + OM) * CC_{wt} / (\eta_s f_a 8760 * CF)$$

where CRF = cost recovery factor

$= i / (1-(1+i)^{(-N)})$

i = interest rate (expressed as a fraction per year)

N = number of years over which the wind project is financed

OM = annual operation and maintenance cost as a fraction of the initial capital cost CC_{wt}

CC_{wt} = initial capital cost given as $/kW ($ per kW of turbine capacity)

35 20 year financial gain it shows some financial card which give you some idea about how that varies but, more importantly one has to understand that this calculation of this and some different countries having these are the cost of the per kilowatt hour rate so you can see that wind energy rate but this can be more and more improved by bringing more indirect cost of the wind turbine so if you reduced electricity output by non-wind generator which increases the unit cost of the electricity partly offset by reduction in the need for non-wind generators wasted electricity generation potential so so what is often thought that the addition of wind energy doesn't allow any reduction in the amount or capacity of the other power sources Because, there could be zero wind production near times of peak demand. So, that is very, very important to note. That is the capacity credit of wind is often assumed to be zero. However, this is not. Instead, the amount of non-wind capacity that is needed to be calculated so as to have the same loss of load probability when there is no wind capacity with instead the full non-wind capacity.

So, These are some issues which can affect your cost calculations as well. So, as a result of that, what happens is the small wind penetration, that is small wind capacity compared to the total capacity, the capacity credit is roughly equal to the capacity factor. For example, if you have a 100 MW of wind power capacity is added to a large system and the capacity factor of the wind turbine is only 20%, then the non-wind capacity can be reduced by 20 MW while still having the same overall system reliability. So, that means you need to have some kind of.

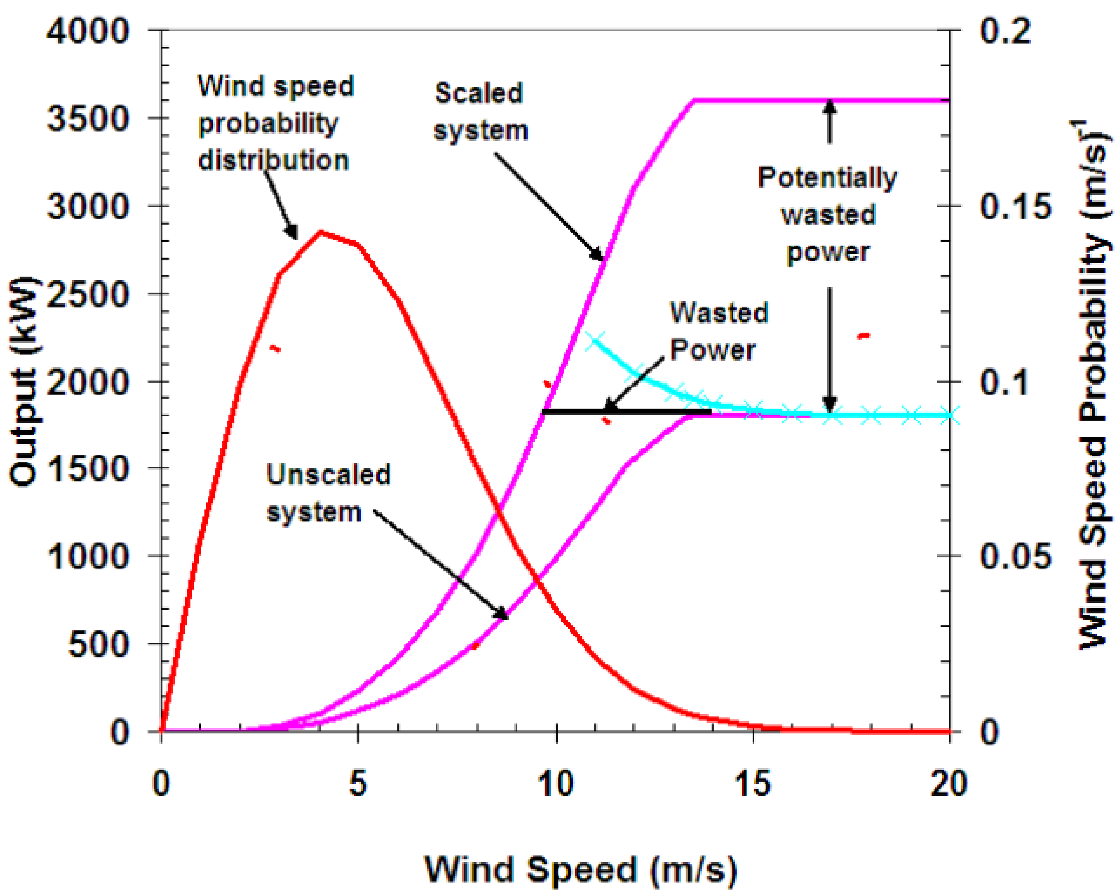
.. So as the wind penetration increases, the capacity credit as a fraction of capacity factor becomes progressively smaller. So, this is an important thing to know. So, at 1000 megawatt and the same 20% capacity factor, the capacity credit might be only 10% instead of 20%. So, the non-wind capacity can be reduced by only 100 megawatt while having the same overall system. The capacity credit for wind is non-zero only because the backup fossil fuel power plants are themselves not 100% reliable as seen in the next slide.

which you can see here. The capacity credit for wind as a function of the wind penetration capacity factor. So, this gives you an idea about wind penetrations and all these things, how these things vary. This is another graph of capacity credit for wind as a function of wind penetration and the degree of geographical dispersion of the wind turbines. you can see how these things are, very obviously these are the things which are important in a sense when you are talking about the system level capacity, so, let us try to recap things so the addition of wind means the existing fossil fuel power plant is useless with increase the wound cost however if you use less fossil fuel power plant Due to the non-zero capacity carried from wind, other indirect costs of the wind include wasted wind electricity potential due to need to maintain a minimum fossil fuel output, reduction in the efficiency of the fossil fuel power plant when wind is added, whether it is operating at lower average load or less efficiently or large swingings in output.

So, what one has to do actually develop a smart wind farm, developing the ability to model the 3D air flow through an entire wind farm, not just around a single isolated wind farm. Optimize the size of individual wind turbine within a wind farm. Development techniques to sense the real air flow through the wind farm. Actively modulate the air through the wind farm. And so, as to maximize the total wind farm electricity production.

So, what you could do is basically adopt some strategies which are some innovative strategies to mitigate the other issues so that you can improve the overall performance and things like that. And there is some strategies to best load wind energy. Oversized wind pumps compared to transmission link can give capacity factors at the 0.6 to 0.7. Compressed air energy storage. Use of dispatchable loads with pumps in direct heating or cooling system. So, if you see this oversizing concept, so this is varying with the wind speed. This is the output in kilowatt. This is the wind speed probability.

So, here is the wasted power, potential wasted power. so, this is on scaled system this is scale system wind speed probability distribution. So, all these things if you put together then you can have a nice picture about, so, if you look at the cost natural gas comment cycle has 660 dollar, 1640 says to because the this one is, This is the time required for the amount of primary energy saved by the wind turbine to offset the total primary energy required to produce the turbine. So, obviously save primary energy per year, electrical energy produced per year divided by the efficiency of the power plant that would otherwise be used to produce electricity. Generally speaking, calculated payback times for wind turbines are 2 to 8 months.



The payback time would be significantly longer if the components need to be transported thousand kilometer or more by truck and things like that. Noise and impacts on birds and bats. So, the bird mortality is miniscule compared to many other human cause of bird deaths. Noise level at distance of 50 meter is less than the typical background level in a home. Impacts on bats need to further study.

So, obviously these are, one can think about the environmental impact. Okay. So, what we can conclude here is that how much wind energy capacity would we need globally as a part of carbon-free 100% renewable energy system? So, that's the question. So, when you look at the overall system, their system level operations, some issues, logistical issues, you have operational issues, design constraints, So, how much we need to really produce to cater to the demand of the complete energy chain so that we can come out of this dependency on the fossil fuel based energy output. And the reason is that this requires a lot of research.

research in every aspect, not only the improving the turbine performance, not only improving the mitigate the variability in the electricity productions, their policy, energy policy, utilization policy, government level norms or policies everything is going to contribute towards achieving this complete goal. okay, so now what we will do We'll try to go slowly in the deeper of this discussion of this particular topic. So, what we would now continue to discuss, look at the other aspect of the things, or rather into the mechanics of wind. and then how the atmospheric boundary layer and other things are going to impact that. So, what we would talk about here is essentially we are talking about here is the mechanics of wind motion.

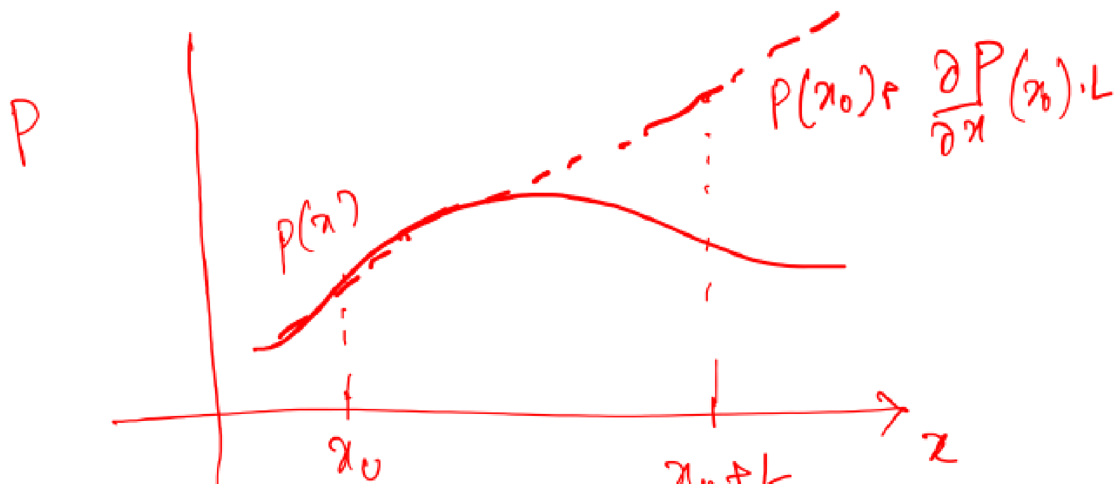
So, now There are. Different influences. That. Lead to have this wind motion.

Obviously to note. Few of them. So, you can have. Pressure. Difference.

You have. Wind motion duty. Due to. Poor release force. You have. centrifugal force, then you have friction. So, primarily one can or broadly categorize these are the major contributor or major influencing factor. I would say the main influencing factors to have the wind motion so how the pressure gradient actually affect we can simply, let's say, we start with the pressure gradient so we can simply look at that using a simple simple example of a cylinder, let's say, we say that this is a simple cylinder where we say this is the length l and we can say at this phase this is the area, let's say this is x naught this is x naught plus l then pressure at this is p of x naught and this side is p of x naught plus l, so, volume would be length into area and obviously your mass is rho length into area which is m, so, what is happening is that so if i put this thing in let's say the plot of pressure with, let's say, length then I have X naught then something X naught plus L, so, I can have some variation and something it can go like that so this is P(x) curve So, at this location it would be here, P x0 plus del P by del x at x0 into L.

So, what happens here is that the pressure varies in base and time, so, that means p is function of x and time this pressure unit is Pascal which is Newton per millimeter so, and we all know the standard atmospheric pressure is one zero one three two five Pascal. okay so, So, what happens is that here the pressure gradient causes net force on air mass. Let's say F would be the net force. So, then we can say that this is area into p x naught minus area into p(xnaught) plus l. So, this we can approximate as area into p(xnaught) area into p(xnaught) into l.

So, which is minus a del p by del x at x naught into l. So, what we can get the acceleration due to pressure gradient. So, let's say if we say that acceleration due to pressure gradient if it is A then we can write as an del p by del x at x naught by rho which is meter per second so one can put this back and write that so you get this acceleration due to pressure gradient second point that we can say that for your least force okay which is primarily due to the rotation of earth. So, let's consider a point on the surface of earth in Freiburg. This point is moving towards the east and consider another point near the north pole it is also moving towards the east.



$$F = A \cdot P(x_0) - A \cdot P(x_0 + L)$$

$$\approx A \cdot P(x_0) - A\, P(x_0) - A \frac{\partial P}{\partial x} \cdot L$$

$$= - A \frac{\partial P}{\partial x}(x_0) \cdot L$$

But because it is closer to the rotational axis of the earth, it is moving slower to the east compared to the favour. It depends where the point is located on earth's surface. Now you imagine that wind moving from north pole towards South. Okay. As it moves further south, the ground is moving faster and faster towards the east, causing the ground to slide away from the wind.

Okay. So, this is what one can draw a picture, let's say, like this. This is the center. So, this is viewed from let's say viewed from above the north pole so with east rotation so let's say this is rotation omega zero, okay, what happens is that as we said that the when it is viewed from the perspective of the ground, it appears that the wind is bending or accelerating towards the right like this. This is the rotation. So, that means what we are trying to say, wind is moving from north to north towards south.

As it moves towards south, the ground is moving faster and faster towards the east. So, that's what caused this slide. And if you look at from the perspective of the ground, So one can view this is the wind is bending or accelerating towards the right. This is primarily called Coriolis effect.

This is primarily due to the rotation of the... This rightward acceleration applies to the wind blowing in all horizontal directions. However, in southern hemisphere, the wind would accelerate to the left instant. This Coriolis effect, this can be regarded as either a virtual force or an acceleration. So, if we put an force here, then 2m, omega naught, v aE zero so accelerate to omega naught vaE so here vaE 0 is the geotropic wind velocity so the coreless force this depends on latitude p which means there is no correlation on the equator so, what, we have so that means no police force on the equator so what we have is two omega naught sine phi video which is del p by del x into 1 by rho so we get vaEo equals to 1 by 2 rho omega naught sine phi into del p by del x so, this is what you obtain as an geostrophic wind velocity so the idea is that this wind motion when they are happening that also how or what kind of motion you get and what are the so obviously these factors like pressure gradient coral dispose these are going to impact and how they are impacting this this is what we are discussing so that can tell you how this wind motion is also varying different country to different country because their geographical location is different.

viewed from above the North Pole.

$$F = 2m\omega_0 V_{GEO}$$

$$a = 2\omega_0 V_{GEO}$$

$V_{GEO} \rightarrow$ geostrophic wind velocity.

So, $a = 2\omega_0 \sin\phi \, V_{GEO} = -\frac{\partial p}{\partial x} \cdot \frac{1}{\rho}$

$$V_{GEO} = \frac{1}{2\rho\omega_0 \sin\phi}\left(-\frac{\partial p}{\partial x}\right)$$

Okay. We'll continue this discussion in the next session.