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The Phenomena of Wake Effect in Wind Turbines

Examination paper in the subject of Renewable Energies

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Declaration of the Authorship

I Kanza Nassabi hereby declare that I have written the present Examination Report independently and have used no other than the specified aids. The places of the housework that were taken from the other sources in the wording or meaning are indicated by indications of origin. This also applies to drawings, sketches, pictorial representations and sources from the Internet.

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1 Introduction

The wind has always been an important energy source operated by humans. For more than 3000 years, this energy was used to move ships with sailboats, as well as pumping water and grind grain with windmills. At the start of the 20 century, Denmark was the first to connect an electric generator to a windmill and produce electrical energy instead of mechanical energy. Also The first wind turbine has been elaborated at that time.
At the end of 1990, wind energy has become one of the powerful renewable energies, for example, its total production of energy in the world has gone from 12.6 TWh in 1997 to 169.3 TWh in 2007, it was an exponential augmentation of 29.6% per year. However, there are always challenges when it comes to growth of energy, especially for offshore wind energy, trying to comprehend and minimize wake losses in wind farms.
The effect of wake loss, which is removing energy from wind passing through the blades that causes reduction of wind speed behind the turbine which creates an increasing of turbulence intensity that will make a bad influence on the performance of downwind turbines, the wake loss can go between 10-20% of the power generated by the front row turbines [1, p. 2].
The wake loss keeps on expanding when the rotor turns and the generator starts to produce electrical power, the flow going out from the turbine is less that the one upfront, also the rotation of the blades adds turbulence, which is based on the initial wind speed and turbulence, and one operation after another makes the wake even grow vastly.

2 Wake effect

Wake effect is the change of the wind speed. Wake turbulence is caused by the impact of turbines on each other. It is a parameter which is very potent especially when it comes to wind farms.
The wake effect is one of the phenomena responsible for the reduction of power production. It can decrease by up to 60% for an individual downstream turbine, while for an entire wind farm, it can be as much as 54% of power reduction. Annually, the cumulative revenue losses that the wake effect can cause is ranging between 20 to 30 % [2].
The propagation of the wake moving downstream is a function of the turbulence caused by the atmosphere, and another by the turbine itself, other parameters in the equation which are the wind speed, and the wind direction. All of them combined can result in the occurring of the wake meandering also in the atmospheric stability.

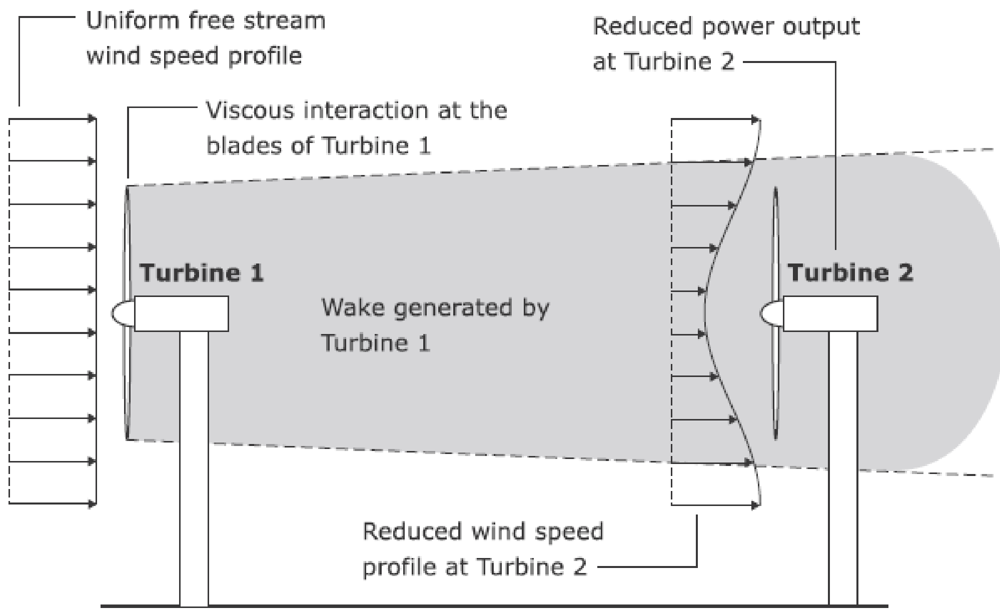

Figure 1 :The phenomenon of aerodynamic coupling between two wind turbines aligned with the free stream wind.

1.1 Impact of wind speed on wake effect

Wake effect is the effect of removing energy from wind passing through blades. Therefore, a reduction of wind speed behind the turbine will occur. This effect is a parasitic turbulence that is generated by the turbine itself.

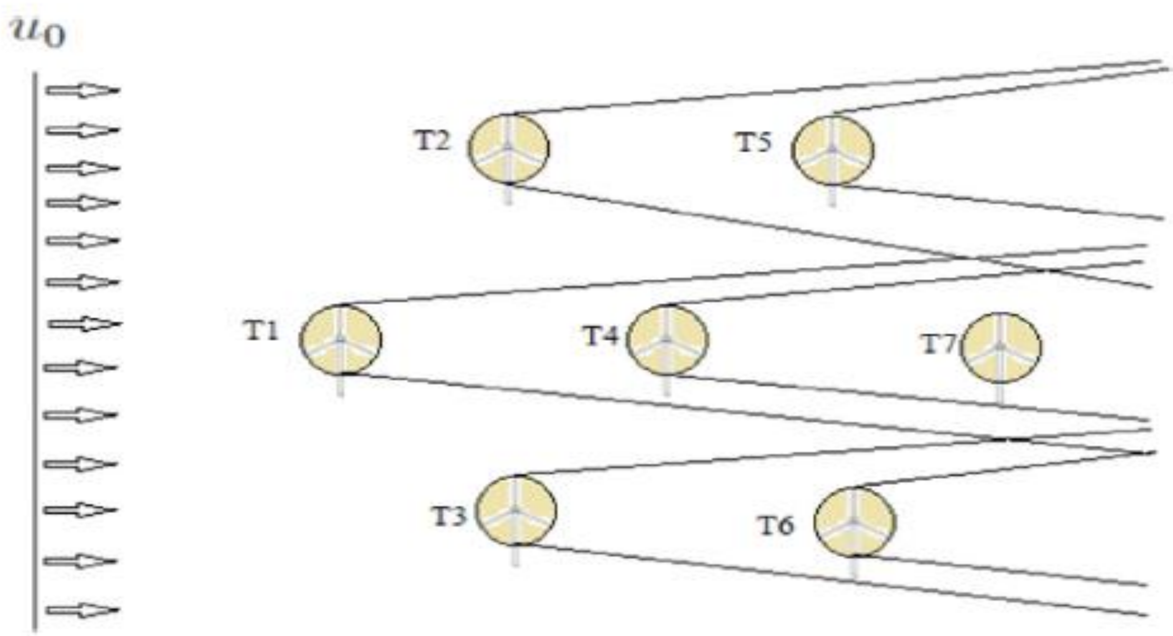

Figure 2 :Jensen’s Multiple wake effect in wind farm *[3]*.

For example, for the first row of turbines T1, T2, T3, the wind moves smoothly through the blades, these turbines are facing a free stream velocity, then a random type of air pressures will be created behind the turbines which is going to cause a disturbed air flow for the next row, for T4, T5, T6 however a single wake effect is operated on them, that will result in decreasing the wind speed, and it keeps getting lower from one row of turbines to another behind it. Like the wind turbine T7 is working in multiple wake effects because two wakes are facing it, one from the upstream turbine T1 and the other from T4.The calculation of the wind speed deficit at the point of the wind turbine T7 has been done by using the equation $v_i = v_o \left[1 - \sqrt{\sum_{i=0}^{N_t} \left(1 - \frac{v_i}{v_o}\right)^2}\right]$, it is the sum of the kinetic energy deficit of each wake to the kinetic energy of the mixed wake at that position. Whereas s=0, which means the velocity in the wake behind the rotor, will be written as $U_o = U_\infty \sqrt{1 - C_t}$.

2.1 Tip Speed Ratio

Tip Speed Ration or TSR, it depends on the number of blades in the wind turbine rotor. The wind turbine rotor needs to turn faster whenever there is fewer number of blades, in order to extract maximum power from the wind. The design of the rotor blade plays a huge role in its efficiency as well as the increasing of the optimum values of the TSR which means more power can be generated. If the TSR is too small, the wind turbine tends to slow down or ever stall. If the TSR is too high, the turbine will spin very fast through the turbulent air, therefore, power will not be optimally extracted from the wind, that will make it highly stressed that it creates a risk of structural failure, because the air won’t be able to flow through the blades, meaning the efficiency will go down because the wind will appear to be facing a solid wall. Tip is the end of the blade, and it is the one that travels the maximum distance, it covers the longest distance in the circle per any giver amount of time. Therefore, the tip velocity is the maximum speed. The TSR indicates how fast the turbine rotates compared to the speed of the wind getting though the blades.

$$TSR = \frac{Tip\ speed\ of\ blade}{Wind\ speed}$$

Wind turbines are designed with optimal TSR to extract as much power out of the wind as possible. To avoid that the rotor will turn too slowly or too quickly.

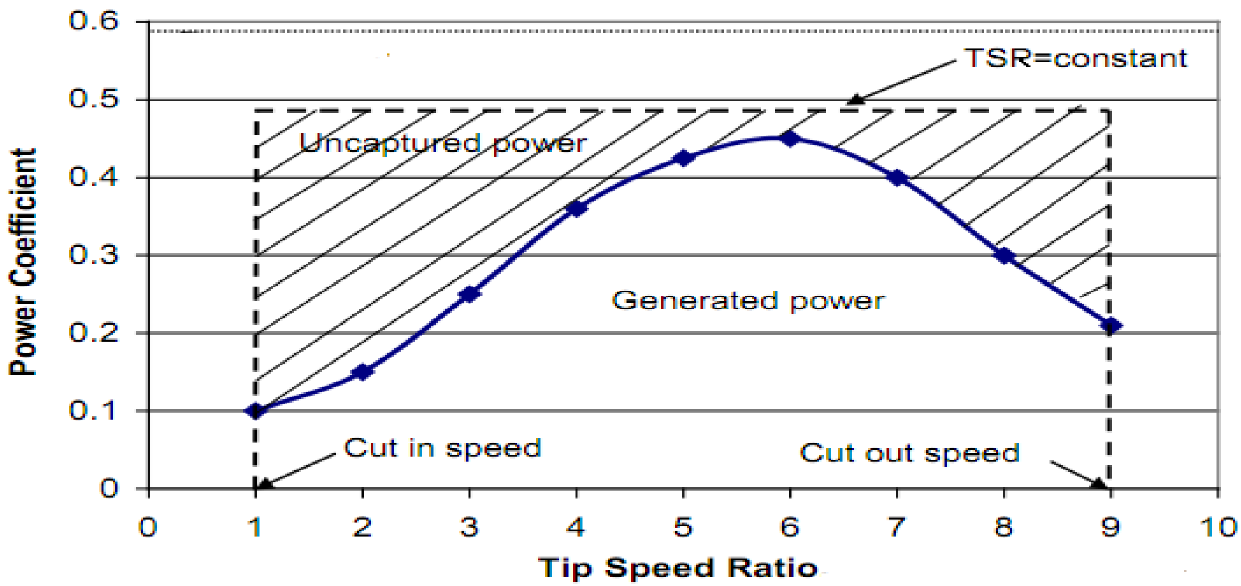

Figure 3: Power coefficient as a function of TSR for a two-bladed rotor. [4, p. 33]

3 Wake effect models

Understanding and analyzing wake losses has led to create complex models, they go from fast to analytical to simple CFD-based models.

1.1 Jensen wake effect model

The widely known analytical model is Jensen, its glory is due to its simplicity and practicality. The model presents an equation for the wake deficit, which is based on the wind deficit in the wake of a turbine. Jensen adopted two assumptions: first, conservation of the cross-stream integral of the velocity deficit, and second, the velocity deficit is a function of the distance x downstream of the turbine.

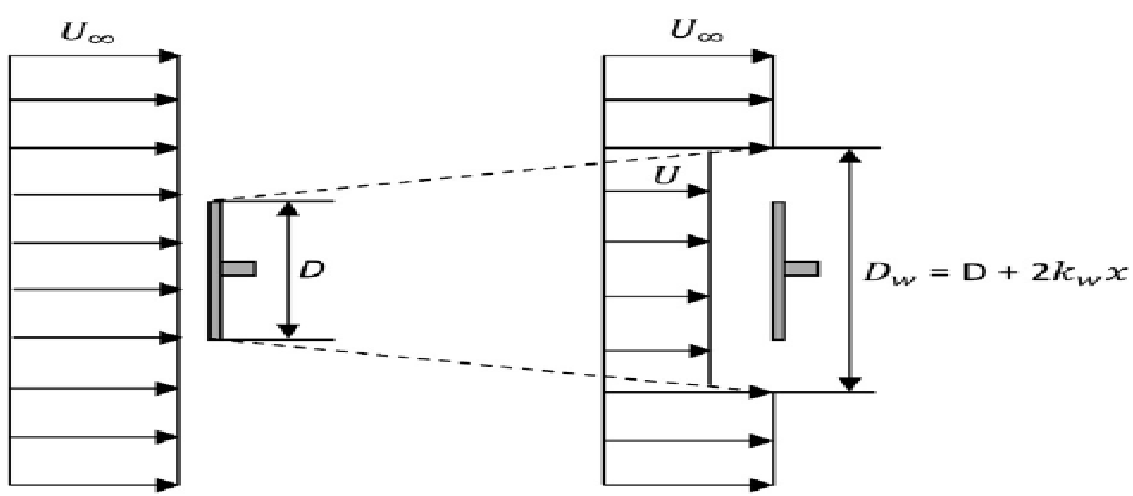

Figure 4:Wind speed profiles for the Jensen model *[1, p. 3]*

The only pertinent variable in Jensen model is x, it is an expression of multiple turbine diameter D, also the wake is considered to be axis-symmetric and has a defined edge which means the wind speed and the wind speed deficit along y and z axis are uniform inside the wake and equal to 0 outside of it.

$$D_w = D_w(x) = D\left(1 + 2K_W \frac{x}{D}\right)$$

The Jensen model estimates the hub height wind speed downstream of a turbine δ at a distance x, which is exposed to an undisturbed wind speed U_∞, when subjected to a hub height inflow wind speed U_{in} as

$$\delta(x) = \frac{U_\infty - U_{in}}{U_\infty}$$

$$\delta(x) = \left\{1 - \frac{U_{in}}{U_\infty}\sqrt{[1 - C_t(U_{in})]}\right\}\left(\frac{D}{D + 2K_w x}\right)^2$$

When C_t is the thrust coefficient and K_W is the wake decay coefficient

2.1 Gaussian wake effect model

The Gaussian distribution is based on both distance x and radial distance r. the model is on the assumption of that the wind speed deficit is following this distribution like it is illustrated in *Figure 5*.

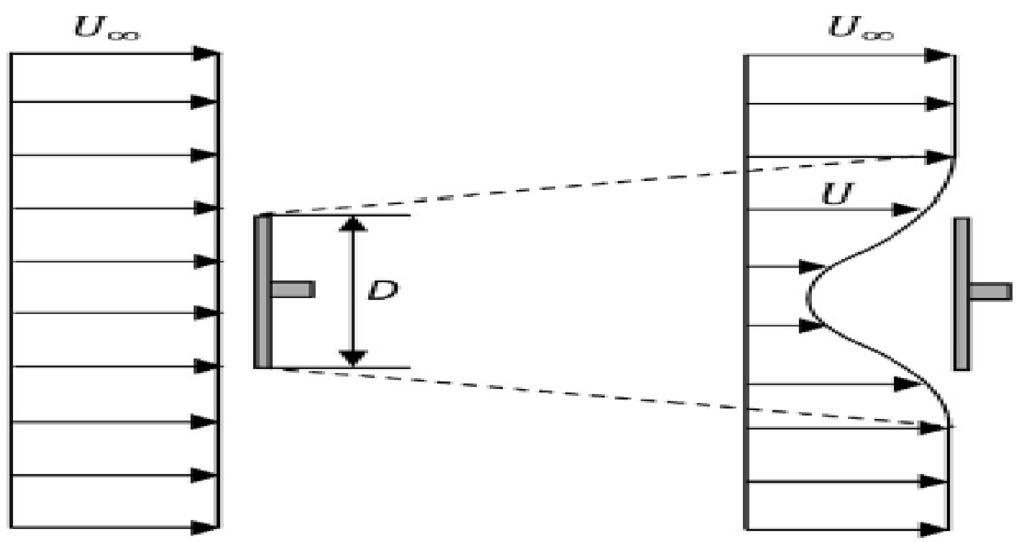

Figure 5: Wind speed profiles for the Gaussian model *[1, p. 3]*

The Gaussian model developed by Bastankah and Porté-Agel is a step forward of the Jenson model because it is taking into consideration two coordinates y and z axis, first represents the spanwise and z the vertical coordinates. The wind speed deficit is given by the following equation

$$\delta = \delta(x, y, z) = \delta_{hub}\ exp\left\{-\frac{1}{2\left(k * \frac{x}{D} + \varepsilon\right)^2}\left[\left(\frac{z - z_h}{D}\right)^2 + \left(\frac{y}{D}\right)^2\right]\right\}$$

Where:

$$\delta_{hub} = \delta_{hub}(x) = 1 - \sqrt{1 - \frac{C_t U_{in}}{8\left(k * \frac{x}{D} + \varepsilon\right)^2}}$$

and z_h is the hub height of the wind turbine

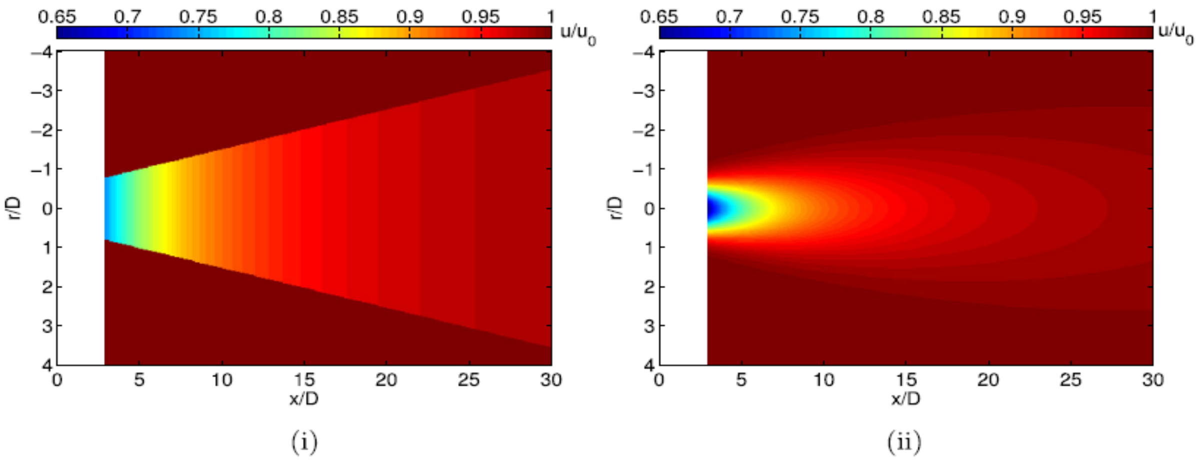

Figure 6:Wake development of a single wind turbine calculated by (i) Jensen's model and (ii) GWM.

The models can be compared by means of wind speed deficit. In Figure 6,two big differences can be spotted as results of each model on predicting wake development, it is shown that in radial axis, Gaussian's model predicts a continuous distribution and a higher velocity deficit compared to Jensen's model, whereas, it predicts a discrete distribution of velocity deficit.

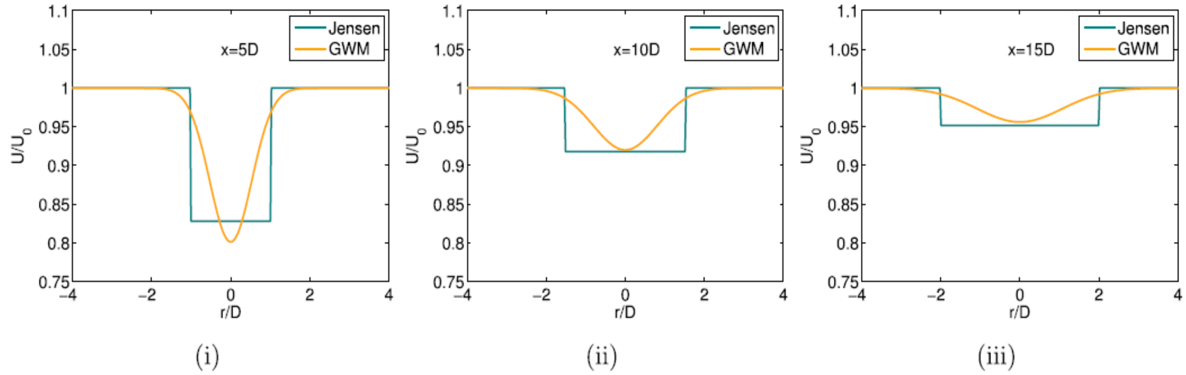

Figure 7:Comparison of the velocity deficits predicted by both models at downstream distances of (i) 5D, (ii) 10D and (iii) 15D from the turbine rotor.

One more third difference is illustrated in Figure 7, where it can be seen that by using Gaussian's model, a fast recovery of the velocity deficit in the radial direction, as the radial distance gets bigger from the center of the wake, while Jensen's model presents the characteristic top-hat shape. The illustration is shown when the velocity deficit is predicted at 5D, 10D and 15D downstream of a turbine rotor.

While Jensen wake model is one of the most popular models among engineering applications on capturing the overall flow behavior behind a wind turbine, it lacks one more flow characteristic which is taking into account the radial dependence of the wake. Thus, it comes the Gaussian's wake model by including a radial direction which will cause the power prediction of a wind farm to be less sensitive to the wind direction.

4 Park Effect

When the wake effect is applied, the first row of turbines will slow down the turbines behind them, each one will cause the one behind it to have more wake and more turbulence. So in order to reduce energy dissipation in the wake of a wind turbine, the turbines supposed to be located from each other as far as possible in the prevailing wind direction, this way, the energy losses will be minimized.

1.1 Extended version of Jensen wake model

Park wake model is the extended version of Jensen wake model. It was developed to improve the efficiency of capturing enough information about aerodynamic phenomena and accuracy. It is designed to study the interaction between multiple wakes on the velocity, assuming that the sum of kinetic energy deficits of all relevant wakes is equal to the kinetic energy deficit at any point in the wind field [2, p. 8].

With its simplicity, that is explained in assuming a linearly expanding wake with a velocity deficit that is only dependent on the distance behind the rotor [3, p. 3]. The park wake model has been approved to be able in predicting the power production in wind farms with a relative error between 0.1 to 15.9% across a range of wind direction [2, p. 8]. It is assumed in the original version of Katic et al [5, p. 8], that the reflection of the original rotor is an underground rotor. So the interaction of the wake is considered in this version.

To obtain the efficiency of a wind farm and the accuracy, four mechanisms' effects are combined together and are taken into account

- Directly upwind rotor wakes.
- Reflected upwind "underground rotors".
- Shading upwind rotors, located left or right of the directly upwind rotor.
- Reflected shading upwind rotors, located left or right of the wind direction.

The equation below, represents the estimation of the velocity deficit at the nth turbine which is calculated by getting the local wakes.

$$\delta_n = \left(\sum_{i=1}^{n} {\delta_i}^2\right)^{\frac{1}{2}} \text{ where, } \delta_n = 1 - \frac{U_n}{U_0}.$$

In case of infinite row of turbines, a model was executed by Jensen to estimate the velocity deficit in such a situation. U_{inf} is taken as the velocity at the last partition.

$$\frac{U_{inf}}{U_o} = 1 - \left(\frac{2a}{1-2a}\right)\left(\frac{f}{1-f}\right) \text{ where, } \quad f = \left(\frac{1}{1+2\alpha D_r\, x}\right)^2$$

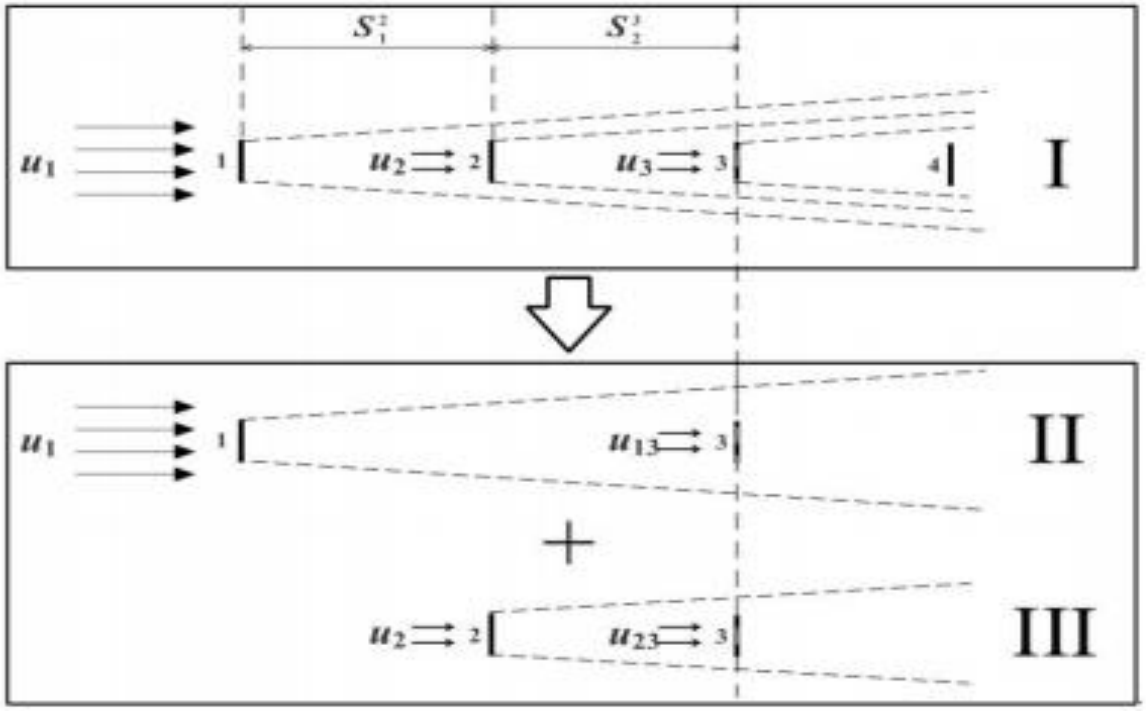

Figure 8 : Schematic diagram of three overlapping turbine wakes. The simulation of the inflow velocity

In *Figure 8* , it is seen a schematic diagram of typical wake superposition with a row of four turbines. The wind turbine 3 is positioned in the area for the upwind turbines 1 and 2. To cpmpute the velocity distribution before turbine 3 in scenario I, first a superposition needs to be applied and divided into two scenarios II and III. The wake deficit cause by Turbines 1 and 2 have to be calculated separately first then be added as the total loss caused by the upwind turbine.

2.1 Infinite Park wake model

When the effects of the four overlapping wakes in the park wake model is taken into account, the total deficit δ_t is estimated as the quadratic sum of four type of wakes.

$$\delta_t = {\delta_i}^2 + {\delta_{ii}}^2 + {\delta_{iii}}^2 + {\delta_{iv}}^2$$

The equation has been solved analytically by Pena and Rathmann in the way below:

$${\delta_i}^2 \approx \frac{{\delta_0}^2}{(1+2\alpha s_r)^3}\left[\frac{1}{2(1+2\alpha s_r)} + \frac{1}{6\alpha s_r}\right];\ {\delta_{ii}}^2 \approx \frac{{\delta_0}^2}{128\left(\frac{h}{D}\right)^3}\left[\frac{1}{4\left(\frac{h}{D}\right)} + \frac{1}{3\alpha s_r}\right];\ {\delta_{iii}}^2 \approx \frac{{\delta_0}^2}{16(s_f)^4}\left[1 + \frac{\frac{s_f}{s_r}}{\alpha}\right];$$

$${\delta_i}^2 \approx \frac{{\delta_0}^2}{16(s_f)^4}\left[\left(1 + 4\left[\frac{\left(\frac{h}{D}\right)}{s_f}\right]^2\right)^{-2} + \left(\frac{\frac{s_f}{s_r}}{\alpha}\right)\left(\frac{1-\left[2+4\left(\left[\frac{h}{D}\right]s_f\right)^2\right]^{-\frac{3}{2}}}{6\left[\frac{\left(\frac{h}{D}\right)}{s_f}\right]^2}\right)\right];\ \text{where } \delta_0 = \left(1 - \sqrt{1 - C_t}\right)$$

The deficit δ_0 represents the initial wake deficit, s_r is the dimensionless stream-wise separation between turbines. $s_r = \frac{x}{D}$ and $s_f = \frac{y}{D}$, whereas y being the cross-wind turbine-turbine distance.
Jensen did not consider the contribution of vortex shedding, this being neglected resulted in taking the wake behind the wind turbine as a turbulent wake only since the impact of the tip vortices is ignored. Knowing that vortex shedding is only applied in the near wake regions, makes Park wake model strictly applicable in the far wake regions.

5 Disposition of wind turbines in a Park

In order to mitigate losses caused by the wake effect, an approach was employed, and it consists in siting wind turbines in a way that there will be a distance and an appropriate space between two adjacent machines in the predominant wind direction [2].
The turbine in the back must have a lower energy content leaving it, than the wind arriving in front of it, since it needs to generate electricity from the energy in the wind. There will always be a wake behind the turbine because it will cast a wind shade in the downwind direction, presented by a long trail of wind that is slowed down and quite turbulent compared to the wind that was in front of the turbine.
Therefore, to avoid turbulence around the turbines downstream as much as possible, wind turbines are put in a park and spaced out by at least three rotor diameters from one another. The rule of thumb is used to dispose the turbines in wind parks, for the ones that are apart in the prevailing wind direction, the space is between 5 and 9 rotor diameters, while the ones that are in the direction perpendicular to the prevailing winds, they are apart by 3 to 5 diameters. In *Figure 9* , there are three rows of five turbines each in a typical pattern, the dots represents the turbines, as it is shown the ones apart in the prevailing wind direction are spaced by 7D whereas the others in the direction perpendicular to the prevailing winds are 4D away from each other.

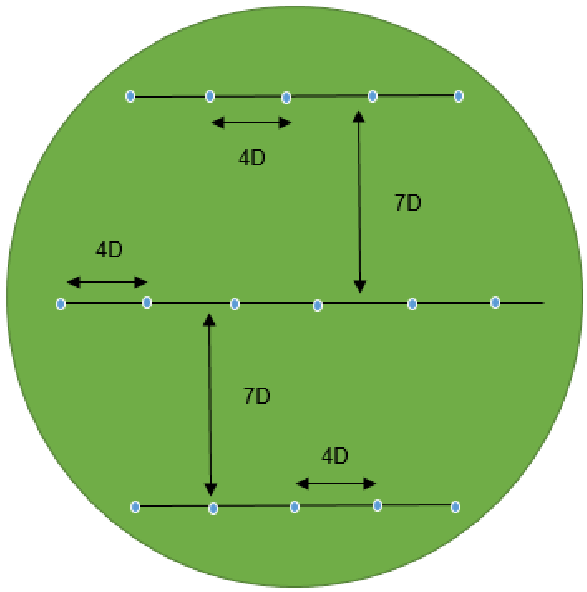

Figure 9 :Park Layout

6 Vortex shedding

1.1 Explanation

Vortex shedding is a phenomenon when the vortices are shed from side to another when air flows around an object. Where there is a generation of an alternating low pressure on the downwind side of the structure which is going to give a rise to a fluctuating force at the angles to the wind direction, the force is quite low and not good enough to accelerate the structure to a good amount, especially if the object is heavy. The effect of vortex shedding is generated by lateral forces of the wind on an object immersed in a laminar flow. In another meaning, the wind flow can produce patterns of vortices in a cyclical form, which results in rising an engineering challenge for slender structures. As a matter of fact, like the example of the collapse of Tacoma Narrow's bridge in 1940, USA.

Operating on the vortex shedding phenomena has a huge impact on structural failure and fatigue on the structure also a well noticed increase in drag and lift fluctuations, as well as acoustic noises. These consequences are important because it is causing significant vibrations along with resonance if the frequency of the periodic driving force on the same spot of the frequency of the oscillation [6, p. 1].

The frequency of the shedding f_s depends on the shape of the body of the object, the velocity of the flow, as well on the surface roughness. And it is given by the famous Strouhal-Reynolds expression, $f_s = \frac{0.2V}{D}$ [7, p. 639], the proportionality constant 0.2 is called the Strouhal number and it is a function of the Reynolds number. V is the velocity of the flow, while the D is the diameter of the cylinder.

2.1 Control of vortex shedding by feedback control methods

There exist multiple methods to control the vortex shedding and the wake structure, and to avoid the unsteady loads of the object. These methods are divided into two categories passive ones which trigger the geometry of the body studied and make modifications on it, they are simpler in implementation due the non-need of external energy. The next category is the one that are active, and it depend on the external energy that affect the fluid flow.

In this paper, one active method will be presented, the control of vortex shedding by feedback control method. Which consists on using a sufficient sensor and an actuator in order to prevent the vortex shedding at Reynolds numbers and to put the wake in a stable mode.

The method of Park et al, try to change successively the control input according to the output which is the response of the flow system, since it is an active method.

Roussopoulos and Monkewitz in 1996 managed to use a nonlinear model for suppressing the vortex shedding in cylinder wakes but only at the spanwise spot of the sensor for long cylinders, the feedback control of Karmen vortex shedding was used for Re~47.Using a Proportional Integral Differential (PID) controller is another method to reach the goal of annihilation of the vortex shedding occurring behind the structure.

Son et Al came to the conclusion that the Proportional P control vary according to the phase shift and the sensing position. Which makes it a valid method to control the vortex shedding and get rid of it. The more the increase in the proportional gain the more the intensification of the decrease in velocity fluctuations in the wake and the strength of vortex shedding, However the disadvantage of a large gain is it can cause the instability of the system.

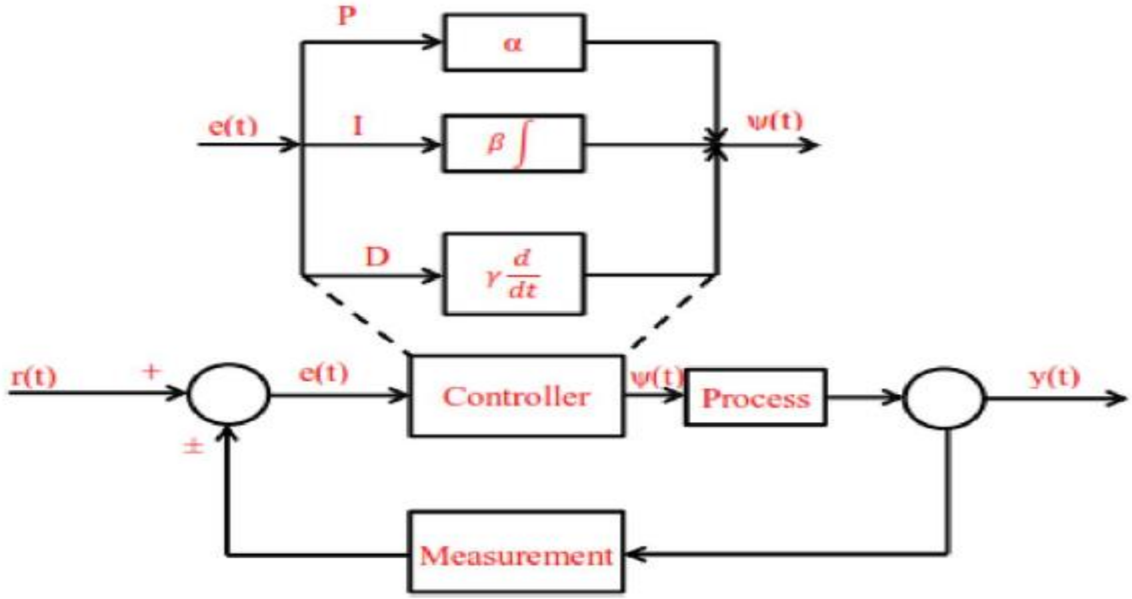

Figure 10 :Block diagram of the PID control, see e.g. Son et al.(2011) [8, p. 5].

InFigure 10, ψ(t) is the control input, e(t) represents the error while α, β and γ are proportional, integral, differential gains, respectively. r is the reference input, y is the system output. Son et al.(2011) [8, p. 5]used I control and D control to raise the chances of decreasing the lift fluctuations and the mean drag also velocity in case the P control was not enough and did not completely annihilate the vortex shedding. For Zhang et al.(2004), it was the only study that used PI and PID controllers to control the flow over an object. The PID was for the reason to decrease the vibration amplitude and stream wise velocity fluctuations [8, p. 5].

7 Modification of local weather

In the regions of wind farms, there is a warming effect that is causing temperature to rise by one degree Celsius. It occurs in areas beyond where wind farms are installed however with only a small increase.

This change in climate is due to the effect of wind turbines on both horizontal and vertical atmospheric circulation. The huge wind turbines locally change the temperature because of the change of wind's flow movement. The turbulences created by the turbine around the sides of it as the tip rotates, manages to make a mixture going between the wind in different directions which increase the temperature in the area.

Those effects generate heat and moisture in the atmosphere, and that affect the climate. This kind of impact happens instantly in a direct way, and from now to 10 years after, wind power will affect the weather more than coal or gas. However, for the next thousand years, it will be the cleanest comparing to the two sources, coal and gas. The impact is receiving serious reflections on decarbonizing the energy system.

8 Conclusion

In this exponential age we are living in, wind energy has been a good solution to reduce greenhouse gas emissions while keeping progress on electricity production. It is indeed one of the cleanest technologies in our globe. However, using wind turbines has an effect applied on it that it is stopping it from being the first in the list when it comes to energy production. In this paper, the wake effect of wind turbines has been presented, defining the factors that come into the equation of wake effect, like the impact of the wind speed and the turbulence that is caused by the atmosphere, as well as the importance of the tip speed ratio in extracting as much power as it a wind turbine could and that based on the tip speed of its blade and the wind speed as well. After that, for analyzing and predicting the wake losses, two models has been discussed and compared. The Jensen wake model taken as a simple model and the Gaussian wake model taken as a developed version of Jensen wake model. While the first based on a discrete distribution and the second a continuous one. And as Jensen has taken a step forward and made the Park wake model was able to predict the power production in wind farms, it works on a way for treating multiple wakes instead of one applied on a turbine. Then, infinite park wake model in case of multiple wakes overlapping each other has been compiled in this paper. As a part of solution for the wake effect, a disposition of wind turbines has been suggested and modeled in function of the diameter of the rotor of the turbine. The phenomena of vortex shedding have been explained, as well as mentioning the method of the feedback control as a solution for the annihilation of this phenomena. This method can be an effective one with the development of the smart materials and intelligent sensors and actuators techniques, and that what made it very popular. The last point to trigger was the effect of wake in turbines and its role on the modification of the local weather.

The prediction of wake losses in a wind farm is difficult because it is based on a complex, non-linear phenomena. A lot of factors comes to the equation when the wind hits the blades of a turbine such as wind speed, wind shear, turbulence intensity, aerodynamic properties of the airfoils in the blades and pitch angle of each blade. Each one of these factors are not easy to simulate.

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