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Modelling and Simulation of Wind Power System Considering Wake Effect Using DigSILENT

[1] Modu Abba Gana, [2] Abdulkadir Ali Warde, [3] Abdullahi Bukar, [4] Muhammad Musa
[1, 2, 4] Department of Electrical and Electronics Engineering, University of Maiduguri, Nigeria
[2] Department of Physics, Federal University Gusau, Nigeria

Corresponding Author: **Modu Abba Gana**

Abstract

The increasing demand for electricity, coupled with the depletion of fossil fuel sources, has accelerated the integration of renewable energies into conventional power generation. Wind energy, recognized for its environmental benefits, faces challenges related to the wake effect resulting in decreased wind velocity downstream of wind turbines (WITs). This turbulence adversely affects power generation efficiency, necessitating the optimization of wind farm layouts (WFALO) to mitigate operational and maintenance costs. This article employs DigSILENT for modeling and simulation, considering wake effects to enhance wind power system efficiency. The wake effect involves a reduction in wind speed and turbulence downstream of WITs, impacting neighboring turbines. Optimizing WFALO requires meticulous consideration of factors such as elevation, wind speed, and hub height. Current techniques often fall short due to computational complexities. The article introduces wake effect models, categorizing them into hydrodynamic and domain models. The Jensin model is highlighted for its simplicity and accuracy in predicting wake effects. Mathematical formulations for non-wake, full wake, partial wake, and multiple wake effects are presented. The impact of wake effects on wind farm output power is analyzed, demonstrating potential power losses of 10-15%. Wind farm designs with uniform or multiple WIT specifications pose challenges in optimization algorithms due to computational complexities. The study emphasizes the importance of incorporating wake effects into wind farm design, considering turbine spacing, control algorithms, and rotor designs. A 15 MW wind power system is simulated in DigSILENT, revealing a significant reduction in wind speed and power output due to wake effects. The outcomes underscore the need for ongoing research in wake modeling and prediction methods to optimize wind farm layouts and operational strategies, promoting cleaner and sustainable power sources.

Keywords: Wind Power, Wake Effect, DigSILENT, Modeling, Simulation, Wind Farm Layout Optimization

Introduction

Depletion of fossil fuel sources and the escalating demand for electricity have prompted the emergence of various renewable energies alongside conventional power generation. While wind energy is recognized for its cleanliness, the wake effect poses a challenge described as the decrease in wind velocity when it traverses a wind turbine (WIT) rotor, leading to turbulence. This turbulence, often referred to as the wake effect, adversely impacts the efficiency of power generation. Consequently, optimizing the layout of wind farms (WFALO) becomes crucial, as suboptimal designs can result in decreased output power, heightened operation and maintenance costs, and accelerated wear and tear, limiting the lifespan of WIT components.

The adverse effects of turbulence, such as increased wear on components like gearboxes due to variable wind speeds, necessitate strategies to retard the deterioration rate and extend the lifespan of WITs. Approximations suggest that the wake phenomenon can reduce wind farm (WFM) power output by 10 -15 percent. To address this, careful consideration of factors like elevation of the WFM, speed of the wind, direction of the wind, and height of the hub is essential during the planning process to minimize the impact of the wake effect (WKE) and optimize energy production (Beşkirli and Haklı 2018) [1].

Effectively managing, if not eliminating, the WKE involve meticulous consideration of the geo - location and position of fixing each turbine. Minimizing the wake effect within a confined area is crucial for maximizing wind farm output power. However, the present techniques for establishing the premier number and locations of WITs in a wind farm present Challenges. Despite efforts to reduce the wake effect, they often fall short due to computational complexities and constraints (Gao *et al*., 2016) [3].

Wind farm designs commonly either employ uniform specifications for WITs or utilize multiple specifications to formulate WFALO, offering flexibility and robustness to the system. However, the use of multiple specifications introduces challenges in optimization algorithms due to the multitude of parameter values, leading to computational complexities (Fang and Yan 2020) [2].

To tackle this issue, meticulous attention to elements such as the elevation of the WFM, speed of the wind, direction of the wind, and height of the hub is crucial in the design phase. This helps reduce the impact of the WKE and enhance energy production efficiency.

Modeling of Wake Effect

The wake effect on a wind turbine (WIT) has two primary impacts: Wind speed reduction and turbulence, as shown in Fig. 1.

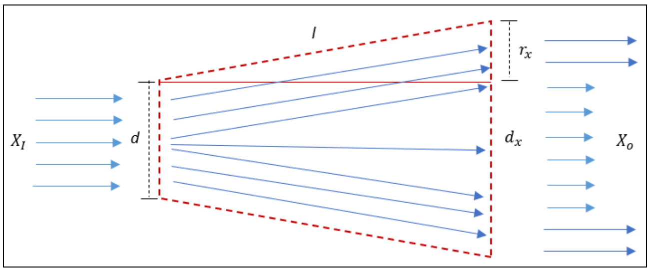

Fig 1: Wake effect on Wind Turbine

The boundary of the wake, like a cone shape figure, results in a linear expansion downward from the up and downstream wind speed (x_o) and (x_i) respectively. The speed of the wind within the boundary reduces the distance between adjoining WITs. This reduction in speed of the wind affects all WITs under the wake effect, with intensity varying based on the proximity to the wake effect source. Closer proximity results in greater intensity, while greater distance leads to reduced intensity. To mitigate power losses and operational costs, it is essential to model the WKE, determining the appropriate speed x_i with known surrounding speed and direction of wind.

Wake effect (WE) models are generally categorized into hydrodynamic models, and domain models. Examples of hydrodynamic models include the Jensin model, Ainsle model, and Larsin model. The Jensin model depicts a linear expansion characteristic behind upstream WITs, resulting in decreased wind speed within the wake boundary. The Ainsle model employs a parabolic eddy cohesion imitation, suitable for dynamic WIT analysis, albeit requiring more time for solutions. The Larsin model, a semi-analytic model, considers non-wake (NW), partial wake (PW), and full wake (PW) scenarios, resembling the Jensen model. Among these, the Jensin model is widely used for its simplicity and accuracy (Chen *et al*.,2016) [6], (Xue *et al*., 2020) [12].

Mathematical formulations for the Jensin model are briefly outlined below. In the WE modeling, scenarios include non-wake effect (NWE), full wake effect (FWE), partial wake effect (PWE), and multiple wake effects (MWE) on a single WIT (Kuo *et al*., 2018) [8].

Non-wake effect

In the non-wake effect scenario, the wind turbine is outside the wake boundary. Meaning the wind speed in all turbines are equal and there is no deficiency of the wind velocity. This scenario is mathematically expressed as in equation 1 (Gaumond *et al*., 2014) [5].

$$x_i = x_o \tag{1}$$

Full Wake Effect

In the full wake effect scenario, the wind turbine is completely within the boundary of single wake effect, mathematically expressed as in equation 2 (Shakoor *et al*., 2016) [11],

$$x_i = x_o\left(1 - \frac{2f}{1+\gamma\left(\frac{Z}{R_1}\right)^2}\right) \tag{2}$$

Where;

f is the induction factor of the axial in the interval of 0.2 – 0.4

$\gamma$is the entrainment constant which specifies the rate at which the boundary of the wake expands relative to X.

and expressed as in equation 3;

$$\gamma = \frac{0.5}{ln\left(\frac{H}{H_0}\right)} \tag{3}$$

Where;

H is the height of the hub

H_0 is the height at which the speed of the wind is zero and it varies according to the terrain. For normal terrain H_0 is 0.3m.

Partial Wake Effect

In this case, the blade partially lies within the wake limits. Some parts of blade are influence by the uphill wake of the turbine. Partial wake effect is mathematically expressed as in equation 4;

$$x_i = x_o\left(1 - \frac{2f}{1+\gamma\left(\frac{Z}{R_1}\right)^2}\right)\frac{A_{pwk\,i}}{A_{twk}} \tag{4}$$

Where;

$A_{pwk\,i}$ is the area of the rotor under partial wake effect

A_{twk} is the total area of the rotor

Multiple Wake Effect

Finally, a wind turbine is affected by numerous wake effect from both up and downstream turbines. The total wake effect in such case is mathematically expressed as in equation 5;

$$x_i = x_o\left(1 - \sqrt{\sum_{j=1}^{m_i}\left(1 - \frac{2f}{1+\gamma\left(\frac{Z}{R_1}\right)^2}\right)}\right) \tag{5}$$

Where;
m represents the WIT with wake effect.
Additional equations of significant importance for analytical purposes include equations for downstream rotor radius *(Rd)*, rotor radius *(Rr)*, and thrust coefficient *(Ct)* and are expressed as in equations 6,7 and 8 (Yan *et al*., 2013), (Zhao *et al*., 2018) [14]

$$R_d = R_T\sqrt{\frac{1-f}{1-2f}} \tag{6}$$

$$R_r = fX + R_T \tag{7}$$

$$C_t = 4f\,(1 - f) \tag{8}$$

As a result of the wake effect, the system experiences power loss of 10 – 15% (ref).

Modeling of Wind Farm Output Power

The potential output power of a wind turbine (WIT) within a wind farm is influenced by various factors related to the available wind speed. Historically, both onshore and offshore wind farms were planned with sparse or straightforward spacing guidelines, and the WITs were positioned along conventional power grids. Though, it has some challenges, this type of layout facilitated the navigation of small or medium-sized WFM. In more recent times, the design of large wind farms has evolved towards a square or rectangular configuration (Kuo *et al*., 2015) [7].

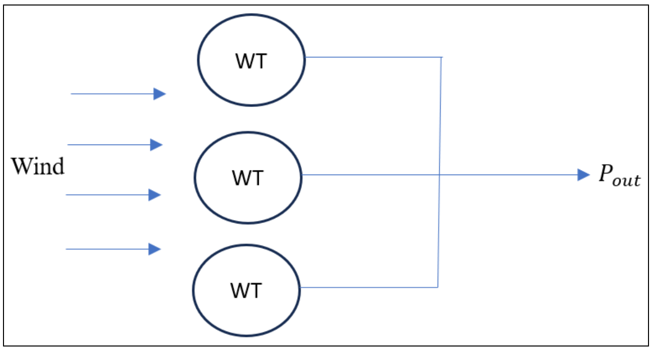

Fig 2: Modelling of Power output

The power output of a turbine is given by equation 9;

$$P_{out} = 0.5A\rho K_P X^3 \tag{9}$$

Where;
K_P represent the power coefficient of the turbine
ρrepresent air density
A is the area of turbine
X is the speed of the wind

Applying Betz theory, the out power for a commercial turbine is 40 percent. Hence, the power output becomes,

$$P_{out} = 0.3X^3 \tag{10}$$

Depending on the speed of the wind at a time and location, the power output is expressed as in equation (11) (Barthelmie *et al*., 2006) [10].

$$P_{out}\,(X) = \begin{cases} 0 & X<3\frac{m}{s} \\ 0.3X^3 & \leq X\leq 12\frac{m}{s} \\ 518kW & \leq X\leq 25\frac{m}{s} \\ 0 & X>25\frac{m}{s} \end{cases} \tag{11}$$

Description of the Wind Farm

The WFM is composed of six turbine generators, each rated at 2.5 MW and operating at 20 kV. The total output power of the WFM is 15 MW. The rotor blade rotation creates a circle with a diameter of 120 meters. The spacing between the generators is 10 times the diameter of the circle formed by the rotating blades. The turbine speed is maintained at 11.5 m/s, and the cut-in and cut-out speeds are defined by equation 11. Additional turbine parameters are detailed in Table 1.

Table 1: Wind Farm Parameters (Shakoor *et al*.,2016) [11]

S. No.	Description	Value
1.	Rated Power Output	25 MW
2.	Terminal Voltage	20 kV
3.	Air Density	1.220 kg/m^3
4.	Wind Velocity	12 m/s
5.	Rotor Inertia	117 Mgm
6.	Length of Blade	50 m
7.	Revolution	15 rpm
8.	TSR (optimal)	8.0
9.	Maximum power coefficient	0.48

Modelling of the Wind Power System

In order to carry out the simulation, the model of the WFM was created in DigSILENT environment as shown in figure 3.

DigSILENT Stands for Digital simulation and electrical network analysis software. It is a leading power system analysis software application for use in analyzing generation, transmission, distribution and industrial systems (Gao and Wang 2020) [4].

It covers the full range of functionality from standard features to highly sophisticated and advanced applications including wind power, distributed generation, real-time simulation and performance monitoring for system testing and supervision. DigSILENT is easy to use, fully Windows compatible and combines reliable and flexible system modelling capabilities with state-of-the-art algorithms and a unique database concept. Also, with its flexibility for scripting and interfacing, DigSILENT is perfectly suited to highly automated and integrated applications (Wang *et al*., 2018) [9],

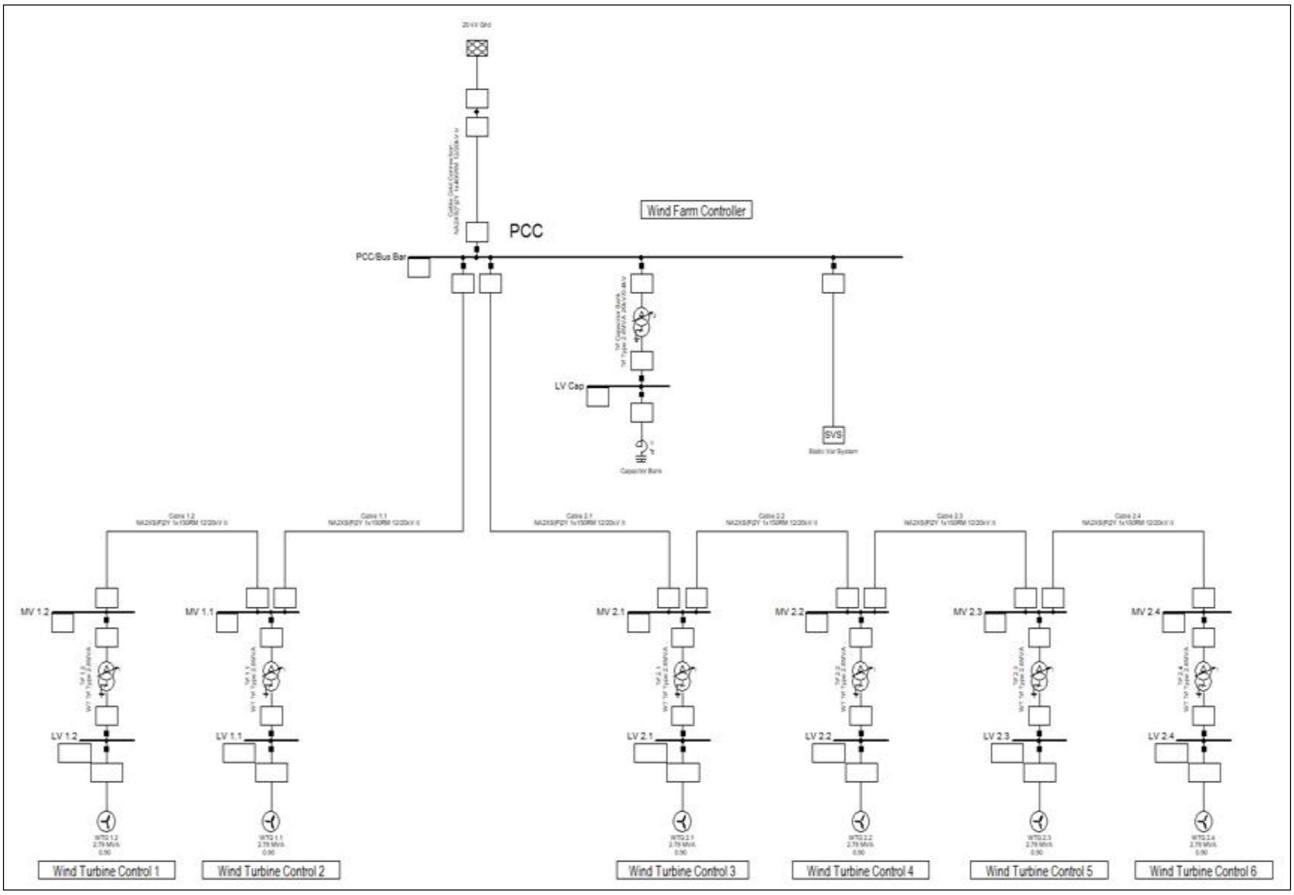

Fig 3: DigSILENT Model of the Wind Power System

Results and Discussion

Three scenario cases were considered in the simulation.

Scenario Case one;

As presented in figure 4, as the wind travelled from first to the last row at the rated speed of 11.5 m/s and travel time of 100 s, as a result of the wake effect a speed decrease of 1.1 m/s was observed.

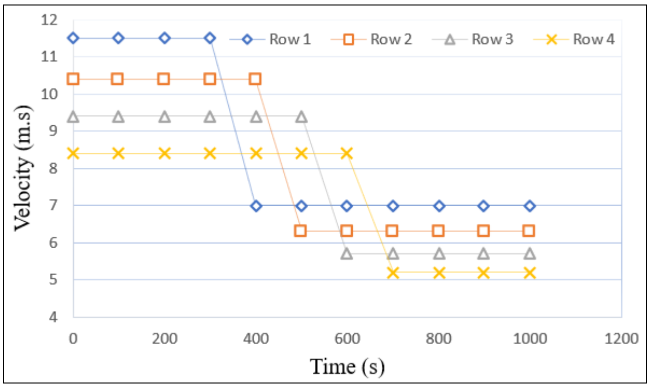

Fig 4: Wind speed of 11.5 m/s with wake effect

Scenario Case two

As depicted in figure 5, the wind speed was increased from 7 m/s to 10 m/s at travel time of 100 s but as a result of the wake effect, the speed equally reduced by 1.1 m/s.

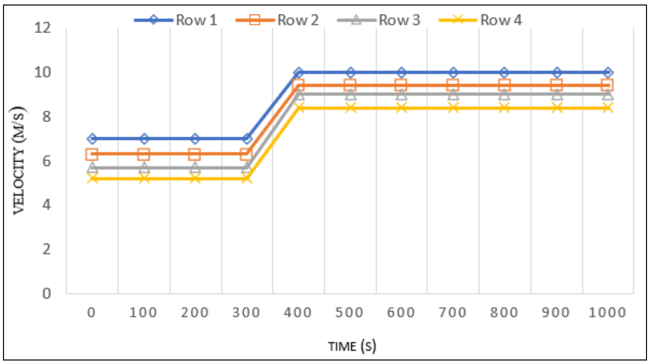

Fig 5: Wind speed from 7 to 10 m/s with wake effect

Scenario Case three

The wind speed was reduced from 10 m/s to 7 m/s at 100 s travel time as depicted in figure 6. However, as a result of the wake effect, the speed was reduced by 1.1 m/s.

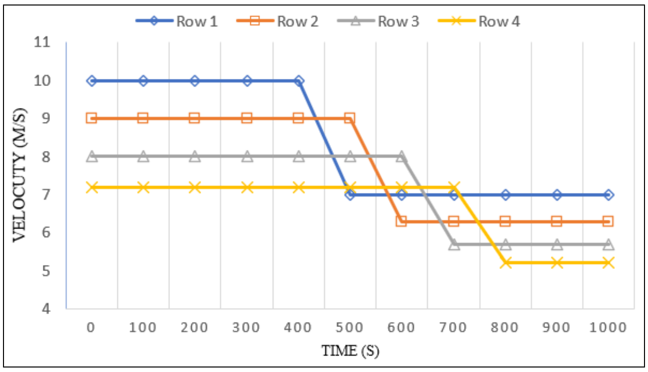

Fig 5: Wind speed from 10 to 7 m/s with wake effect

Table 2: Power Output according to Wake Effect

S. No	Wake Effect	Power Output (MW)	Reduction in Output Power (%)
1.	Non - Wake effect	15	0
2.	Partial Wake effect	12.75	15
3.	Full Wake effect	12.3	18
4.	Multiple Wake effect	12	20

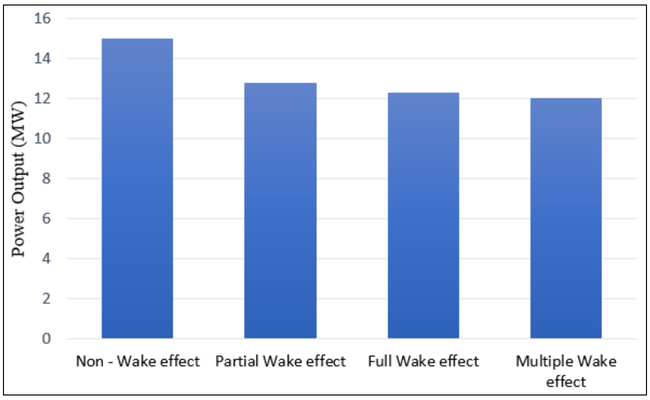

Fig 6: Power Output according to Wake effect

Conclusion

In conclusion, this research has delved into the intricacies of wind power systems with a focused examination on the significant impact of wake effects. The wake effect, characterized by the turbulent flow patterns and reduced wind speeds downstream of wind turbines, emerges as a crucial factor influencing the overall efficiency and performance of wind farms. Through a comprehensive analysis of wake models, experimental studies, and advanced simulations, this research has highlighted the complexities associated with wake interactions in multi-turbine environments.

A 15 MW wind power system, featuring six 2.5 MW-rated wind generators operating at 20 kV, was simulated using the DigSILENT environment. The study aimed to investigate the influence of wake effects on power output by examining three distinct scenario cases. The outcomes revealed a reduction in wind speed by 1.1, 1.3, and 1.5 m/s for the respective cases, resulting in corresponding percentage decreases in power output of 15%, 18%, and 20%. This underscores the significant impact of wake effects on wind turbine performance, demonstrating that the wind speed diminishes progressively due to these effects.

The findings underscore the importance of incorporating wake effects into the design, layout, and operation of wind farms to optimize energy production and enhance the cost-effectiveness of wind power systems. Researchers and industry stakeholders must consider wake mitigation strategies, such as improved turbine spacing, advanced control algorithms, and innovative rotor designs, to minimize the negative impact of wakes on downstream turbines.

Furthermore, the study emphasizes the need for ongoing research and development in wake modeling and prediction methods, as well as advancements in technology to address the challenges posed by wake effects. Collaboration between academia, industry, and policymakers is essential to facilitate the implementation of optimized wind farm layouts and operational strategies that can maximize energy extraction from wind resources while mitigating the adverse effects of wakes.

In summary, a comprehensive understanding of wake effects is pivotal for the sustainable growth of wind power systems. By addressing wake-related challenges and adopting innovative solutions, the wind energy sector can further contribute to the global transition towards cleaner and more sustainable sources of power.

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