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

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Abstract

Increasing demand for electricity, coupled with depletion of fossil fuel sources, has accelerated the integration of renewable energies into conventional power generation in Nigeria. 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 research employs DigSILENT for modeling and simulation, considering wake effects to enhance wind power system efficiency. Mathematical formulations for non-wake, full wake, partial wake, and multiple wake effects were employed. The impact of wake effects on a 15 MW wind farm featuring six 2.5 MW-rated wind generators operating at 20 kV was analyzed in DigSILENT environment considering three scenarios. In scenario one the wind travelled from first to the last row at the rated speed of 11.5 m/s and travel time of 100 s. In scenario two the wind speed was increased from 7 m/s to 10 m/s at the same travel time 100 s. And finally in scenario three the wind speed was reduced from 10 m/s to 7 m/s at the same travel time of 100 s. 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

Keywords: Wind power, wake effect, DigSILENT, modeling, simulation, wind farm layout optimization.

Modélisation et simulation d'un système d'énergie éolienne en tenant compte de l'effet de sillage à l'aide de DigSILENT

Resume

La demande croissante d'électricité, associée à l'épuisement des sources de combustibles fossiles, a accéléré l'intégration des énergies renouvelables dans la production d'électricité conventionnelle au Nigeria. L'énergie éolienne, reconnue pour ses bénéfices environnementaux, est confrontée à des défis liés à l'effet de sillage entraînant une diminution de la vitesse du vent en aval des éoliennes (WIT). Ces turbulences affectent négativement l'efficacité de la production d'électricité, nécessitant l'optimisation de la configuration des parcs éoliens (WFALO) pour atténuer les coûts d'exploitation et de maintenance. Cette recherche utilise DigSILENT pour la modélisation et la simulation, en prenant en compte les effets de sillage afin d'améliorer l'efficacité du système éolien. Des formulations mathématiques pour les effets de non-sillage, de sillage complet, de sillage partiel et de sillage multiple ont été utilisées. L'impact des effets de *sillage sur un parc éolien de 15 MW comprenant six éoliennes de 2,5 MW fonctionnant à 20 kV a été analysé dans l'environnement DigSILENT en considérant trois scénarios. Dans le premier scénario, le vent s'est propagé du premier au dernier rang à une vitesse nominale de 11,5 m/s et un temps de déplacement de 100 s. Dans le deuxième scénario, la vitesse du vent est passée de 7 m/s à 10 m/s pour un même temps de trajet de 100 s. Et enfin, dans le troisième scénario, la vitesse du vent a été réduite de 10 m/s à 7 m/s pour un même temps de trajet de 100 s. Les résultats ont révélé une réduction de la vitesse du vent de 1,1, 1,3 et 1,5 m/s dans les cas respectifs, entraînant une diminution correspondante en pourcentage de la puissance de sortie de 15 %, 18 % et 20 %. Cela souligne l'impact significatif des effets de sillage sur les performances des éoliennes, démontrant que la vitesse du vent diminue progressivement en raison de ces effets.*

Mots-clés : Énergie éolienne, effet de sillage, DigSILENT, modélisation, simulation, optimisation d'aménagement de parc éolien.

زيادة الطلب على الكهرباء، إلى جانب استنفاد مصادر الوقود الأحفوري، تسريع إدماج الطاقات المتجددة في توليد الطاقة التقليدية في نيجيريا. طاقة الرياح، هذا .(WITs) معترف بها لفوائدها البيئية يواجه تحديات تتعلق بتأثير الاستيقاظ مما أدى إلى انخفاض سرعة الرياح في اتجاه مجرى توربينات الرياح الاضطراب يؤثر سلبا على كفاءة توليد الطاقة، مما يستدعي الاستفادة المثلى من مخططات مزارع الرياح للتخفيف من التشغيل والصيانة التكاليف يستخدم للنمذجة والمحاكاة، النظر في آثار الاستيقاظ لتعزيز كفاءة نظام طاقة الرياح. تركيبات رياضية لعدم الاستيقاظ والاستيقاظ DigSILENT هذا البحث الكامل والاستيقاظ الجزئي وتأثيرات الاستيقاظ المتعددة استخدمتتأثير تأثيرات الاستيقاظ على مزرعة رياح بقدرة 15 ميجاوات تتميز بستة مولدات رياح بالنظر إلى ثلاثة سيناريوهات. في السيناريو الأول، انتقلت الرياح DigSILENT بقدرة 2.5 ميجاوات تعمل بسرعة 20 كيلو فولت تم تحليلها في بيئة من الصف الأول إلى الصف الأخير بسرعة تصنيف 11.5 م/ث ووقت السفر 100 ثانية في السيناريو الثاني، تمت زيادة سرعة الرياح من 7 م/ث إلى 10 م/ث في نفس وقت السفر 100 ث وأخيرًا في السيناريو الثالث، تم تخفيض سرعة الرياح من 10 م/ث إلى 7 م/ث في نفس وق ت سفر 100 ثانية. في نفس وقت سفر 100 ثانية. كشفت النتائج عن انخفاض في سرعة الرياح بمقدار 1.1 و 1.3 و 1.5 م/ث فيما يتعلق بالقضايا ذات الصلة،مما أدى إلى انخفاض النسبة المئوية المقابلة في إنتاج الطاقة بنسبة 15٪ و 18٪ و 20٪. هذا يؤكد التأثير الكبير لتأثيرات الاستيقاظ على أداء توربينات الرياح، تثبت أن سرعة الرياح تتضاءل تدريجياً بسبب هذه الآثار

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).

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).

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),

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.

Materials and Method

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.

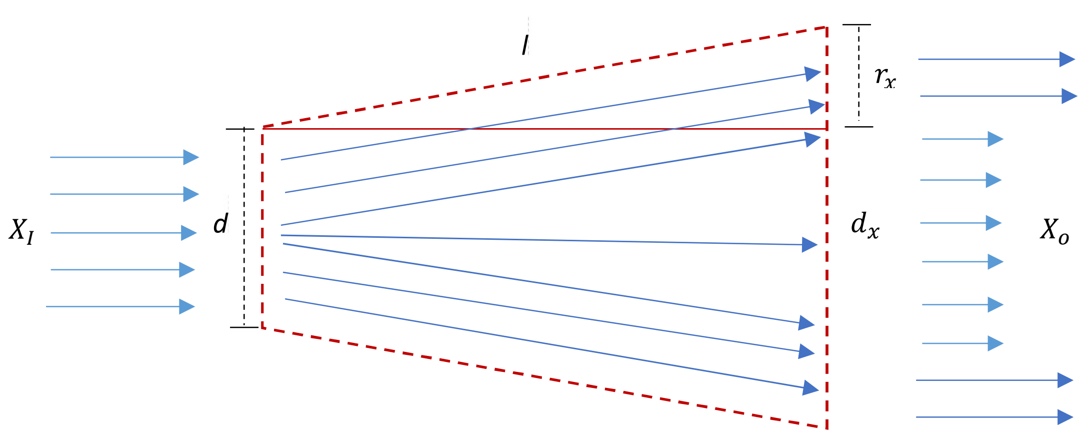

Fig 1: Wake effect on Wind Turbine

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), (Xue et al., 2020)

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).

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).

$$x_i = x_o \qquad (1)$$

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),

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

Where;

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

γis the entrainment constant which specifies the rate at which the boundary of the wake expands relative to X.
and expressed as in equation 3;

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

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;

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

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;

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

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)

$$R_d = R_T\sqrt{\frac{1-f}{1-2f}} \quad (6)$$

$$R_r = fX + R_T \quad (7)$$

$$C_t = 4f\,(1 - f) \quad (8)$$

As a result of the wake effect, the system experiences power loss of 10 – 15% (Yan et al., 2013)

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).

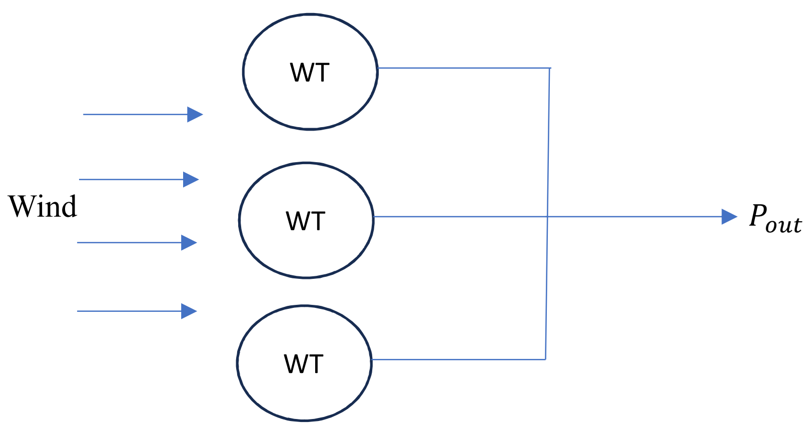

Fig 2: Modelling

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

$$P_{out} = 0.5A\rho K_P X^3 \quad (9)$$

Where;

K_P represent the power coefficient of the turbine

ρ represent 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,

$$P_{out} = 0.3X^3 \quad (10)$$

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).

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

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)

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, short for Digital Simulation and Electrical Network Analysis Software, represents a prominent tool in the realm of power system analysis. It stands out for its comprehensive suite of features catering to the examination of generation, transmission, distribution, and industrial systems (Gao and Wang, 2020).

This software encompasses a wide spectrum of functionalities, ranging from fundamental features to highly intricate applications. These include but are not limited to wind power analysis, distributed generation assessments, real-time simulation capabilities, and performance monitoring for system testing and supervision. DigSILENT boasts user-friendly interfaces, full compatibility with Windows operating systems, and seamlessly integrates reliable system modeling with cutting-edge algorithms and a distinctive database architecture.

Moreover, its adaptability for scripting and interfacing renders DigSILENT ideally suited for highly automated and integrated

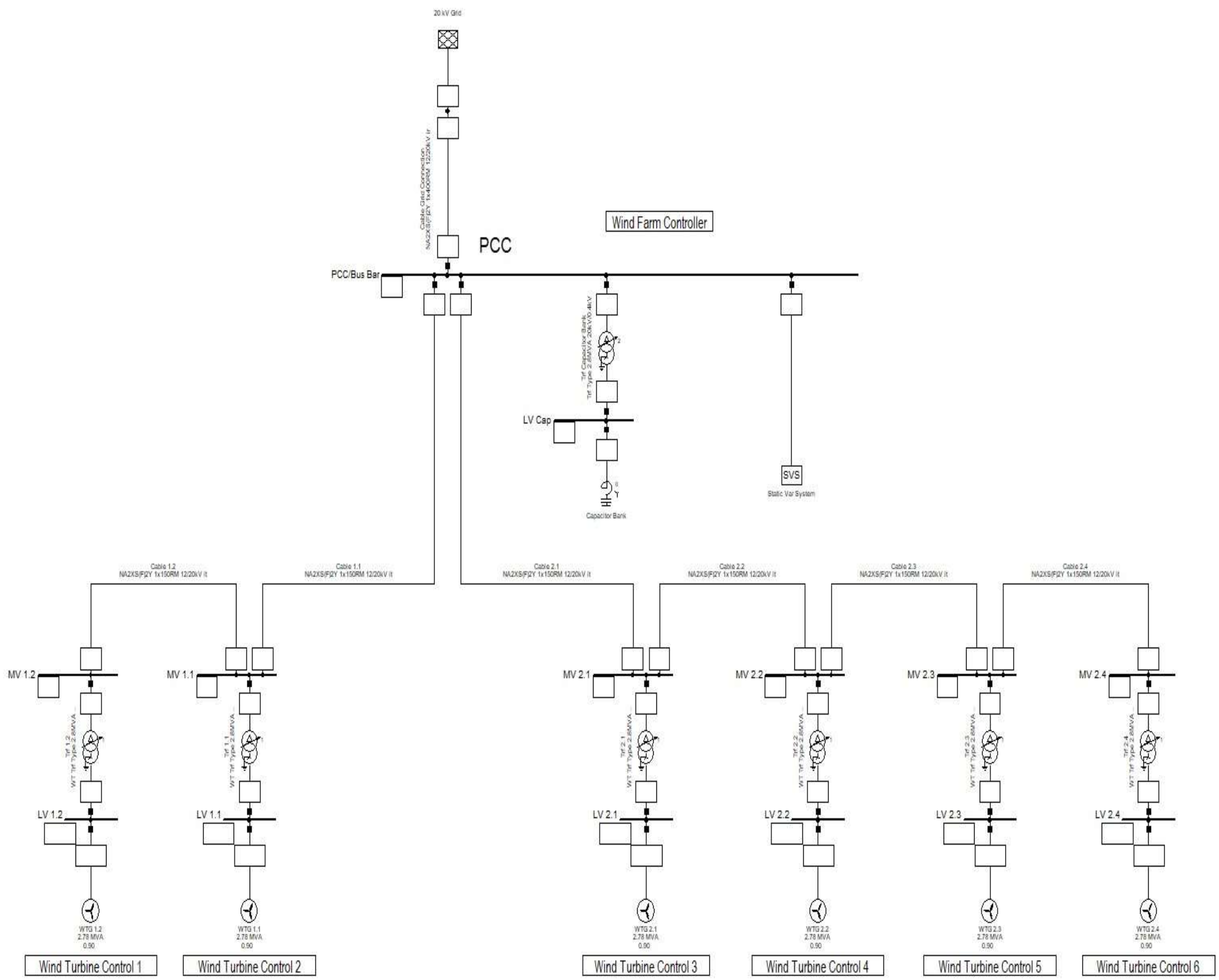

Figure 3: DigSILENT Model of the Wind Power System

Results and Discussion

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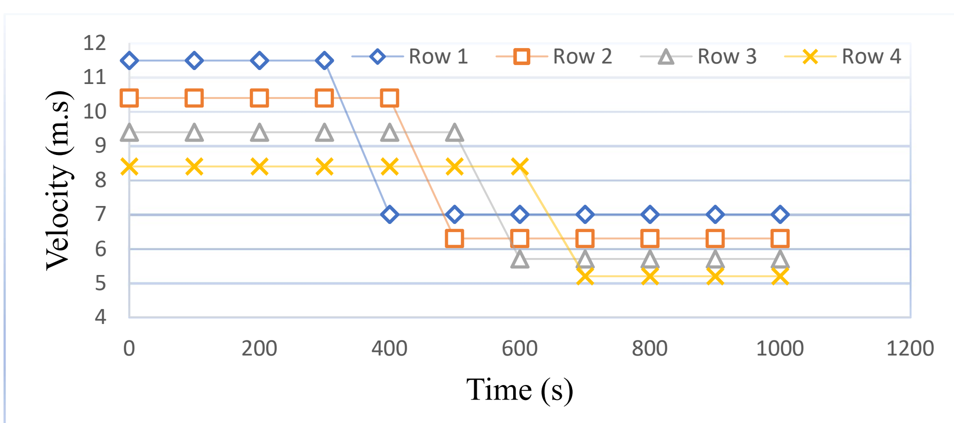
Scenario Case one;

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.

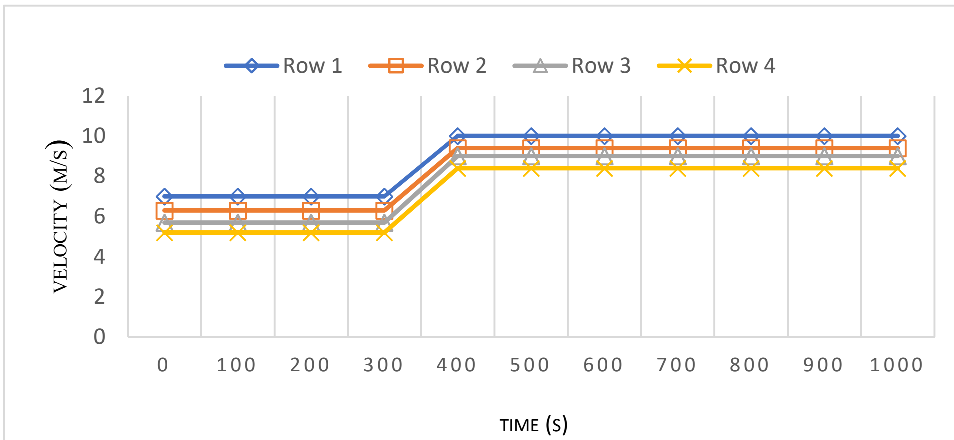


Fig 5: Wind speed from 7 to 10 m/s with wake effect

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.

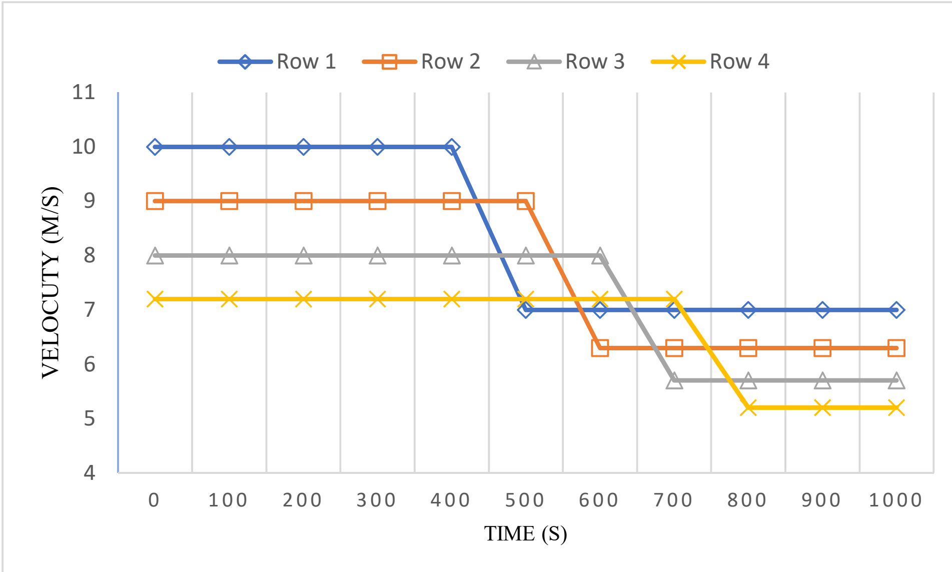


Fig 5: Wind speed from 10 to 7 m/s with wake effect

Discussion

The results of this research offer significant insights into the impact of wake effects on the performance of wind power systems. Across the three scenarios analyzed, it was observed that the presence of wake effects led to a substantial reduction in wind speed and, consequently, a decrease in power output from the wind turbines.

In scenario one, where the wind traveled from the first to the last row of turbines at a constant rated speed of 11.5 m/s, a reduction in wind speed by 1.1 m/s was observed. This resulted in a 15% decrease in power output compared to the non-wake scenario. This reduction highlights the extent to which wake effects can impede the performance of downstream turbines, as the flow becomes turbulent and energy-depleted.

Scenario two examined the impact of an increased wind speed gradient, with the wind speed ramping up from 7 m/s to 10 m/s over the same travel time of 100 s. Despite the initial acceleration, the presence of wake effects still led to a reduction in wind speed by 1.3 m/s, resulting in an 18% decrease in power output compared to the non-wake scenario. This suggests that even under conditions of higher overall wind speed, the detrimental effects of wake turbulence persist and hinder turbine performance.

In scenario three, the wind speed was decreased from 10 m/s to 7 m/s over the same travel time. Here, the impact of wake effects was most pronounced, with a reduction in wind speed by 1.5 m/s and a corresponding 20% decrease in power output compared to the non-wake scenario. This demonstrates that not only does wake turbulence diminish the overall wind speed, but it can exacerbate the loss of energy in situations where the initial wind speed is lower.

Overall, these results underscore the critical importance of considering wake effects in wind power system design and operation. By quantifying the magnitude of power losses associated with wake turbulence, this research provides valuable insights for optimizing turbine placement, layout design, and operational strategies to mitigate the effects of wakes and maximize energy yield. Furthermore, these findings highlight the need for continued research and innovation in wind energy technology to address the challenges posed by wake effects and advance towards a more efficient and sustainable renewable energy future.

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

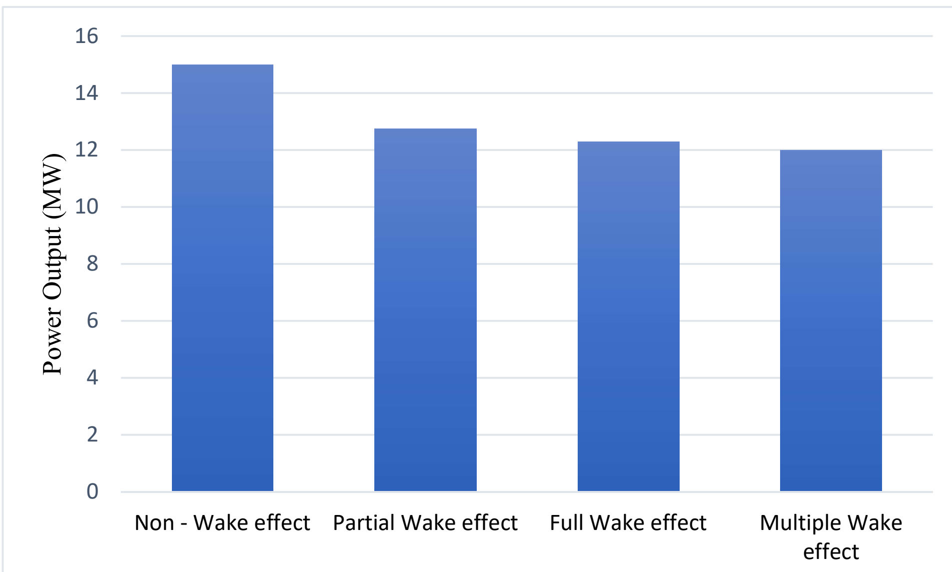


Figure 6: Power Output according to Wake effect

Conclusion

In conclusion, this research has provided valuable insights into the modeling and simulation of wind power systems, with a specific focus on the influential role of wake effects. By utilizing DigSILENT software, the study comprehensively examined how these effects can impact the efficiency and performance of wind farms across varying scenarios.

Through mathematical formulations capturing non-wake, full wake, partial wake, and multiple wake effects, the research highlighted the intricate dynamics at play within wind turbine environments. Specifically, the analysis of a 15 MW wind farm featuring six 2.5 MW-rated wind generators operating at 20 kV elucidated the substantial influence of wake effects on power output.

The findings underscored a notable reduction in wind speed and, consequently, a decrease in power output across the examined scenarios. With reductions ranging from 1.1 to 1.5 m/s and corresponding percentage decreases of 15% to 20%, the impact of wake effects on turbine performance was unequivocally demonstrated.

These outcomes emphasize the critical importance of accounting for wake effects in wind power system design and operation. As evidenced by the results, neglecting these factors can significantly diminish the overall efficiency and energy yield of wind farms. Therefore, incorporating wake effects into modeling and simulation efforts is essential for optimizing performance and maximizing the potential of renewable energy resources.

Looking ahead, future research endeavors may explore additional factors influencing wake effects and their interactions within wind turbine arrays. Moreover, continued advancements in simulation technologies and methodologies will further refine our understanding of wind power system dynamics, paving the way for more sustainable and efficient renewable energy solutions.

In essence, this study contributes to the broader body of knowledge surrounding wind energy and underscores the importance of considering wake effects in the pursuit of a cleaner and more sustainable energy future.

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