# Wind Turbine Wake Interactions At Field Scale An Les

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**Turbine wake interaction \u0026 ground cover effects for onshore wind farms** ***Studying the Wake of Wind Turbines*** **Windfarm visualization** ***Wind Turbine Wake Model*** **Wake Impact on Wind Turbines Explained** **~~Interaction of horizontal-axis turbine wakes~~** **Wind Farm Dynamic Yield Optimization using Reinforcement Learning ¦ AI \u0026 Energy ¦ Giorgio Cortiana** **Downstream Wind Turbine Wake Effects** **Large Eddy Simulation of Wind Turbine Wakes with Yaw Effects** **~~Is Wind Energy Worth It?~~** ***Turbulent Transport in the Wakes of***

***Wind Turbines*** **How to get the most energy out of offshore wind farms** ***Why Do Wind Turbines Have Three Blades? The Tech That Could Fix One of Wind Power's Biggest Problems*** **WIND TURBINE INSTALL! generating OFF GRID POWER from the WIND! LES Wind Farm Site Assessment: 300+ wind turbines \u0026 hilly terrain Simulations about 2D,3D VAWT \u0026 Pelton wheel dynamic mesh 6DOF Ansys Fluent** ***500W Wind Turbine Review ¦ Wind Turbine Free Energy ¦ Urdu/Hindi*** **12. Wind turbine terminology and Components** ***14. Flow and forces around a wind turbine blade***

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**Wind Power Physics**

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**Wind turbine CFD simulation**~~**Let it snow: Understanding wind turbine wake behavior using snow PIV and large eddy simulations**~~ ~~**DTU Wind Energy - Wakes | Educational videos**~~

**~~Nonlinear 3D Soil-Structure Interaction of a Wind Turbine Foundation with DIANA~~**

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**Rotor and Wake Aerodynamics - Course Introduction*HAWT - Wake Turbulence - SixtySec*** **Jason Jonkman - WISE Lecture Series** **Grand Challenges in the Science of Wind Energy Discover how being an original can guide you to Living Full Out** **~~Wind Turbine Wake Interactions At~~**

**The most important structural effect on a wind turbine which is in the wake of a neighbouring machine is fatigue, that is due to the combined effect of increased turbulence, wind speed deficit and shear, and changes in turbulence structure that cause dynamic loading, which may excite the wind turbine structure.**

**~~Wind turbine wake aerodynamics - ScienceDirect~~**

**downstream turbine caused by the interaction of the turbine blades with coherent vortex structures found within the upstream turbine wake. Periodic, stochastic, and transient loads all have an impact on the lifetime of the wind turbine blades and drivetrain. Vortex**

**~~Wind Turbine Wake Interactions - Characterization of ...~~**

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**Wind Turbine Wake Interactions At Field Scale An Les ...**

**As wind farms grow in size and power density, the aerodynamic wake interactions that occur between neighboring turbines become increasingly important in characterizing the unsteady turbine loads and power output of the farm. Turbine wake interactions also impact variability of farm power generation, acting either to increase variability or decrease variability depending on the wind farm control algorithm.**

**Wind Turbine Wake Interactions - Characterization of ...**

**remote sensing, lidar, turbine wakes, wake interactions, atmospheric stability 1 Introduction As wind energy**

**deployment grows, questions arise regarding how wind plants affect the local environment. The 2010 and 2011 field campaigns of the Crop-Wind Energy Experiment (CWEX) [1-3] quantified**

**~~Lidar observations of interacting wind turbine wakes in an ...~~**
**Results from three "Blind test" Workshops on wind turbine wake modeling are presented. While the first "Blind test" (BT1, 2011) consisted of a single model turbine located in a large wind tunnel, the complexity was increased for each new test in order to see how various models performed. Thus the next "Blind test" (BT2, 2012) had two turbines mounted in-line.**

### ~~Wind turbine wake interactions; results from blind tests ...~~

**If the wind farm configuration or wind conditions are such that a turbine rotor is subject to partial impingement by the wake produced by an upstream turbine, then significant unsteadiness in the aerodynamic loading on the rotor blades of the downwind turbine can result, and this unsteadiness can have considerable implications for the fatigue life of the blade structure and rotor hub.**

### ~~Simulation of wind turbine wake interaction using the ...~~

**Effects of Wake Interaction on Downstrea m Wind Turbines Amanullah Choudhry 1* , Jang-Oh Mo 1 , Maziar Arjomandi 1 , Richard Kelso 1 1 School of Mechanical Engineering, The University of Adelaid e ...**

## ~~(PDF) Effects of Wake Interaction on Downstream Wind Turbines~~

**The force F is generated by the wind's interaction with the blade. The magnitude and distribution of this force is the primary focus of wind-turbine aerodynamics. The most familiar type of aerodynamic force is drag. The direction of the drag force is parallel to the relative wind.**

## ~~Wind-turbine aerodynamics - Wikipedia~~

**The accurate modeling of the wind turbine wakes in complex terrain is required to accurately predict wake losses. In order to facilitate the routine use of computational fluid dynamics in the optimized micrositing of wind turbines**

**within wind farms, an immersed wind turbine model is developed.**

**~~Simulation of Wake Interactions in Wind Farms Using an ...~~**

**fidelity representation of the structure and evolution of the wake of a wind turbine rotor and its interaction with other turbines within a wind farm, the fluid dynamics associated with the power losses discussed above can be better understood. Importantly, this may allow the designers of wind farms to explore ways in which to alleviate the adverse effects of interaction, including not only power losses, but also the unsteady**

**~~Simulating Wind Turbine Interactions using the Vorticity ...~~**

## Turbine wake interaction & ground cover effects for onshore wind farms

~~Turbine wake interaction & ground cover effects for onshore wind farms~~

Within the United States, energy production from wind is aimed at 20% of the total energy market by 2030 (USDOE, 2008). As wind turbines reach higher into the atmosphere, rotor diameters increase and wind farms can expand beyond 20 km in length. Understanding the flow dynamics imposed by the atmospheric boundary layer (ABL) and local turbine wake interactions is an essential part of wind farm design and

## ~~THESIS COMPUTATIONAL MODELING OF WIND TURBINE WAKE ...~~

**Wake redirection is a promising approach designed to mitigate turbine-wake interactions which have a negative impact on the performance and lifetime of wind farms. It has recently been found that substantial power gains can be obtained by tilting the rotors of spanwise-periodic wind-turbine arrays. Rotor tilt is associated**

## ~~Evaluation of tilt control for wind-turbine arrays~~

**Furthermore, this work investigates a technique to accelerate the breakdown of wind turbine wakes. The onset of wake breakdown is caused by perturbations that travel along the helical structure of the wake and grow via mutual-**

induction interaction between neighboring vortex filaments. To accelerate wake breakdown, the blade tip vortices are perturbed at different frequencies via trailing-edge flaps located in the outboard region of the rotor blades.

## ~~Predicting Wind Turbine Wake Breakdown Using a Free Vortex ...~~

An experimental PIV study of the vortex interaction in the wake up to = 5 behind a two‐bladed model turbine of = 0.60 m was performed by Lignarolo et al. 16 Their results emphasized the importance of the wake instability caused by a pairwise interaction of the tip vortices on the momentum deficit in the wake, which was shown to be

**strongly dependent on the turbine's tip speed ratio. An ...**

**~~An experimental study on the effects of winglets on the ...~~**
**69 for example the interactions of wake between wind turbines. 70 In a wind farm made up of multiple rows, the downstream wind turbine sees the 71 combined effects of the incoming flow and the disturbance caused by the upstream 72 turbines. This latter flow i.e. the wake, is a region of low velocity fluid coupled with high**

**~~A hybrid actuator disc - full rotor CFD methodology for ...~~**
**Abstract Impacting particles such as rain, dust, and other debris can have devastating structural effects on wind turbines, but little is known about the interaction of such**

debris within turbine wakes. This study aims to characterize behavior of inertial particles within the turbulent wake of a wind turbine and relative effects on wake recovery.

~~Dynamic effects of inertial particles on the wake recovery ...~~

Particularly important is the effect of ABL turbulence on wind-turbine wake flows and their superposition, as they are responsible for considerable turbine power losses and fatigue loads in wind farms. These flow interactions affect, in turn, the structure of the ABL and the turbulent fluxes of momentum and scalars. This review summarizes recent experimental, computational, and theoretical research efforts that have contributed to improving our understanding and ability to predict the ...

Growing concerns about the environmental impact of fossil fuel energy and improvements in both the cost and performance of wind turbine technologies has spurred a sharp expansion in wind energy generation. However, both the increasing size of wind farms and the increased contribution of wind energy to the overall electricity generation market has created new challenges. As wind farms grow in size and power density, the aerodynamic wake interactions that occur between neighboring turbines become increasingly important in characterizing the unsteady turbine loads and power output of the farm.

**Turbine wake interactions also impact variability of farm power generation, acting either to increase variability or decrease variability depending on the wind farm control algorithm. In this dissertation, both the unsteady vortex wake loading and the effect of wake interaction on farm power variability are investigated in order to better understand the fundamental physics that govern these processes and to better control wind farm operations to mitigate negative effects of wake interaction. The first part of the dissertation examines the effect of wake interactions between neighboring turbines on the variability in power output of a wind farm, demonstrating that turbine wake interactions can have a beneficial effect on reducing wind farm variability if the farm is properly controlled. In order to**

balance multiple objectives, such as maximizing farm power generation while reducing power variability, a model predictive control (MPC) technique with a novel farm power variability minimization objective function is utilized. The controller operation is influenced by a number of different time scales, including the MPC time horizon, the delay time between turbines, and the fluctuation time scales inherent in the incident wind. In the current research, a non-linear MPC technique is developed and used to investigate the effect of three time scales on wind farm operation and on variability in farm power output. The goal of the proposed controller is to explore the behavior of an ‘ideal’ farm-level MPC controller with different wind, delay and horizon time scales and to examine the reduction of system power

**variability that is possible in such a controller by effective use of wake interactions. The second part of the dissertation addresses the unsteady vortex loading on a downstream turbine caused by the interaction of the turbine blades with coherent vortex structures found within the upstream turbine wake. Periodic, stochastic, and transient loads all have an impact on the lifetime of the wind turbine blades and drivetrain. Vortex cutting (or vortex chopping) is a type of stochastic load that is commonly observed when a propeller or blade passes through a vortex structure and the blade width is of the same order of magnitude as the vortex core diameter. A series of Navier-Stokes simulations of vortex cutting with and without axial flow are presented. The goal of this research is to better understand the**

challenging physics of vortex cutting by the blade rotor, as well as to develop a simple, physics-based, validated expression to characterize the unsteady force induced by vortex.

We performed numerical simulations of small, utility scale wind turbine groupings to determine how wakes generated by upstream turbines affect the performance of the small turbine group as a whole. Specifically, various wind turbine arrangements were simulated to better understand how turbine location influences small group wake interactions. The minimization of power losses due to wake interactions

**certainly plays a significant role in the optimization of wind farms. Since wind turbines extract kinetic energy from the wind, the air passing through a wind turbine decreases in velocity, and turbines downstream of the initial turbine experience flows of lower energy, resulting in reduced power output. Our study proposes two arrangements of turbines that could generate more power by exploiting the momentum of the wind to increase velocity at downstream turbines, while maintaining low wake interactions at the same time. Furthermore, simulations using Computational Fluid Dynamics are used to obtain results much more quickly than methods requiring wind tunnel models or a large scale experimental test.**

**Aerodynamics of Wind Turbines is the established essential text for the fundamental solutions to efficient wind turbine design. Now in its second edition, it has been entirely updated and substantially extended to reflect advances in technology, research into rotor aerodynamics and the structural response of the wind turbine structure. Topics covered include increasing mass flow through the turbine, performance at low and high wind speeds, assessment of the extreme conditions under which the turbine will perform and the theory for calculating the lifetime of the turbine. The classical Blade Element Momentum method is also covered, as are eigenmodes and the dynamic behaviour of a turbine. The new material includes a description of the effects of the dynamics and how this can be modelled in an**

**?aeroelastic code?, which is widely used in the design and verification of modern wind turbines. Further, the description of how to calculate the vibration of the whole construction, as well as the time varying loads, has been substantially updated.**

**One of the current major challenges in wind energy is to maximize energy production of wind farms. One approach in this effort is through control of wind turbine wake interactions, since undesirable wake interactions can introduce additional mechanical stresses on turbines, leading to early failures and reduce overall energy production of wind farms. To develop control strategies that can minimize wake interactions, it is essential to simulate**

**wake behaviors accurately and quickly. In this work, a fast and accurate turbine wake model capable of modeling turbine wakes under yaw is presented. This model builds upon the work of existing wake models and is capable of producing results comparable to that of conventional full CFD simulations using a fraction of the computational cost. The accuracy and speed of the proposed model allows for the development of real-time turbine control strategies to maximize power output. The results of the proposed model are validated with previous numerical and experimental data found in the literature. Wind tunnel tests were also designed and conducted in order to validate the models' ability to simulate overlapping wakes, a requirement for producing realistic results of a complete wind farm**

**simulation.**

**Wind turbines are one of the most promising renewable energy technologies, and this motivates fertile research activity about developments in power optimization. This topic covers a wide range of aspects, from the research on aerodynamics and control design to the industrial applications about on-site wind turbine performance control and monitoring. This Special Issue collects seven research papers about several innovative aspects of the multi-faceted topic of wind turbine power optimization technology. The seven research papers deal respectively with the aerodynamic optimization of wind turbine blades through Gurney flaps; optimization of blade design for large**

offshore wind turbines; control design optimization of large wind turbines through the analysis of the competing objectives of energy yield maximization and fatigue loads minimization; design optimization of a tension leg platform for floating wind turbines; innovative methods for the assessment of wind turbine optimization technologies operating on site; optimization of multiple wake interactions modeling through the introduction of a mixing coefficient in the energy balance method; and optimization of the dynamic stall control of vertical-axis wind turbines through plasma actuators. This Special Issue presents remarkable research activities in the timely subject of wind turbine power optimization technology, covering various aspects. The collection is believed to be beneficial to readers

**and contribute to the wind power industry.**

**The book encompasses novel CFD techniques to compute offshore wind and tidal applications. Computational fluid dynamics (CFD) techniques are regarded as the main design tool to explore the new engineering challenges presented by offshore wind and tidal turbines for energy generation. The difficulty and costs of undertaking experimental tests in offshore environments have increased the interest in the field of CFD which is used to design appropriate turbines and blades, understand fluid flow physical phenomena associated with offshore environments, predict power production or characterise offshore environments, amongst other topics.**

**Wind energy is becoming one of the most significant sources of renewable energy. With its growing use, and social and political awareness, efforts are being made to harness it in the most efficient manner. However, a number of challenges preclude efficient and optimum operation of wind farms. Wind resource forecasting over a long operation window of a wind farm, development of wind farms over a complex terrain on-shore, and air/wave interaction off-shore all pose difficulties in materializing the goal of the efficient harnessing of wind energy. These difficulties are further amplified when wind turbine wakes interact directly with turbines located downstream and in adjacent rows in a turbulent atmospheric boundary layer (ABL). In the present**

study, an ABL solver is used to simulate different atmospheric stability states over a diurnal cycle. The effect of the turbines is modeled by using actuator methods, in particular the state-of-the-art actuator line method (ALM) and an improved ALM are used for the simulation of the turbine arrays. The two ALM approaches are used either with uniform inflow or are coupled with the ABL solver. In the latter case, a precursor simulation is first obtained and data saved at the inflow planes for the duration the turbines are anticipated to be simulated. The coupled ABL-ALM solver is then used to simulate the turbine arrays operating in atmospheric turbulence.A detailed accuracy assessment of the state-of-the-art ALM is performed by applying it to different rotors. A discrepancy regarding over-prediction of tip loads and an artificial tip correction is identified. A new proposed ALM* is developed and validated for the NREL Phase VI rotor. This is also applied to the NREL 5-MW turbine, and guidelines to obtain consistent results with ALM* are developed.Both the ALM approaches are then applied to study a turbine-turbine interaction problem consisting of two NREL 5-MW turbines. The simulations are performed for two ABL stability states. The effect of ABL stability as well the ALM approaches on the blade loads, turbulence statistics, unsteadiness, wake profile etc., is quantified. It is found that ALM and ALM* yield a noticeable difference in most of the parameters quantified. The ALM* also senses small-scale blade motions better. However, the ABL state dominates the wake recovery pattern. The ALM* is then applied to a mini wind farm comprising five NREL 5-MW turbines in two rows and in a staggered configuration. A detailed wake recovery study is performed using a unique wake-plane analysis technique. An actuator curve embedding (ACE) method is developed to model a general-shaped lifting surface. This method is validated for the NREL Phase VI rotor and applied to the NREL 5-MW turbine. This method has the potential for application to aero-elasticity problems of utility-scale wind turbines.

The second main contribution from this thesis is a proposed Multi-Population Genetic Algorithm (MPGA) simulation model for wind turbine layout optimization which is a long-history research hotspot started from 1983. The optimal

**turbine layout pattern can increase the power generation of the wind farm, reduce the wake interaction between wind turbines,which otherwise would increase dynamic mechanical load and cause higher fatigue load.Many researchers have been working on this topic with different methods, and the proposed MPGA program has been validated by solving the same wind farm optimization issues. More power generation with a lower cost of energy (COE) demonstrates the advancement of this model.For this optimization program, the focus in this thesis goes further. The new proposed wake model is used in this program with a comprehensive cost model, which considers the local wind farm development conditions including labour cost. By using this optimization simulation model, together with**

**wind farm size, wind data and turbine characteristics as inputs,the simulation model can generate the optimal layout for the turbines with total power generations, COE and wind farm efficiency and so on. It is reported that, for the Case of 'constant wind speed of 12m/s with variable wind direction',using the newly-developed Jenson-Gaussian wake model in the MPGA optimization program make the power generation and wind farm efficiency decreased than that of the Jenson's wake model. The power loss caused by wake effect is about 20%, which is in accordance with previous literatures. Three layout patterns can be chosen before the program is started, i.e. aligned, staggered and scatter ones. Besides, the offshore wind developing conditions in Hong Kong are studied. The total water area**

**suitable for offshore wind farm development is determined after considering the local water conditions, wind condition and water area usage purposes. The potential offshore wind farm area in and beyond Hong Kong's boundary (2 km) is about 357.78 km2 (21.68% of the HK's water area). Finally, four typical offshore wind farm sites located at different water areas in Hong Kong are selected. Using the MPGA optimization program, the top ten optimal layout patterns for each potential site are proposed. The Hong Kong offshore wind power potential is reported with the COE and wind farm efficiency. It is estimated that the optimal wind turbine layout separation is 14.5D in prevailing wind direction and 11.0D in cross wind direction (D represent the turbine rotor diameter). The levelized cost of energy (LCOE)**

is calculated in HK$ terms, i.e. 1.474/kWh (aligned), 1.467/kWh (staggered), nd 1.290/kWh (scattered). APG (annual energy generation) is determined to be 40.80{604}10x/y8 kWh (aligned), 40.42 {604}10x/y8 kWh (staggered), and 33.98 {604}10x/y8 kWh (scattered), representing 9.48% (aligned), 9.39% (staggered), and 7.89% (scattered) of the annual electricity consumption for HK in 2012.The results can provide guidance for the government or private developers to develop the offshore wind farms in Hong Kong. In summary,this research project developed a new analytical wake model and proved its practicability as the basic velocity deficits calculation models. The wake characteristics based on the new model are estimated. The newly-developed MPGA optimization program has a good performance on wind turbine layout optimization within wind farm and also, its availability in solving the real-world offshore wind farm turbine micro-siting has been validated. The optimization for Hong Kong offshore wind farm with the offshore wind energy assessment process can provide a new thought and filled the research gaps for the wind farm development and wind energy assessment in this research area.

This thesis focuses on the development of techniques for detection of wind turbine wakes and their consequential impact on wind farm efficiency. Performance in power production of an on-shore wind farm is investigated through SCADA data, while the wind field within and

**around the wind farm is monitored through scanning wind LiDAR measurements and meteorological data. To retrieve these data, a four-month LiDAR field campaign was conducted. The power production of each turbine is analyzed as functions of the operating region of the power curve, wind direction and atmospheric stability. Five different methods are used to estimate the potential wind power as a function of time, enabling an estimation of power losses connected with wake interactions. The most robust method from a statistical standpoint is that based on the evaluation of a reference wind velocity at hub height and experimental mean power curves calculated for each turbine and different atmospheric stability regimes. It is assessed that power losses are larger under stable**

**atmospheric conditions than for convective regimes, which is a consequence of the stability-driven variability in wake evolution. For this wind farm under examination, power loss due to wake shadowing effects is estimated to be about 4% and 2% of the total power production when operating under stable and convective conditions, respectively. However, cases with power losses about 60-80% of the potential power are systematically observed for specific wind turbines and wind directions. The estimated power losses are ascribed to wake interactions by providing evidence of enhanced wind turbulence on downstream wind turbines. These losses are then analyzed from the perspective of the annual energy production, an important parameter for wind farm design and assessment in the wind**

energy industry. WAsP simulations of the wind farm are carried out to validate the estimated losses from the SCADA data. Furthermore, LiDAR measurements are analyzed, confirming that wind turbine wakes recover faster under convective regimes, thus alleviating detrimental effects due to wake interactions. As the initial steps to perform a detailed study and a statistical analysis on wake morphology, this thesis describes the methods of post-processing the LiDAR measurements taken of the wind farm. First, a filtering and realignment of the radial velocity into a time- and wind-dependent reference frame is carried out. Then, different techniques to define the main parameters of wind turbine wakes (such as width and center) are described and discussed. Results show that methods such as the center of gravity, which rely on a fitting that considers several measurement points, provide the most robust approach to define wake characteristics.

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