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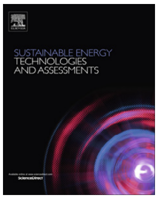

Original article

Wind farms with counter-rotating wind turbines

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ABSTRACT

The objective of this study is to assess the effects of using counter-rotating wind turbines on the performance of a wind farm. Large eddy simulations, coupled with the actuator line model, were conducted to investigate flow through a test wind farm with 48 large-scale wind turbines with the same layout as Lillgrund in Sweden. Two counter-rotating cases were tested; first, an alternate-row wind farm in which each turbine has one rotor, rotating either clockwise or counter-clockwise, with alternating rows of clockwise and counter-clockwise turbines throughout the farm; and second, a wind farm with dual-rotor wind turbines in which each turbine has two rotors, with the first rotor rotating counter-clockwise and the second rotor rotating clockwise. It was found that both counter-rotating configurations were more efficient in power generation than the control case in which all turbines have one clockwise rotor; the alternate-row case was found to produce 1.4% more power and the dual-rotor case was found to produce 22.6% more power than the control wind farm. The wakes of the counter-rotating cases, particularly the wind farm with dual-rotor wind turbines, exhibit different characteristics from those in the control case. These differences are discussed through wind speed distribution, thrust coefficient, and power production of wind turbines.

Introduction

Energy supplies are moving away from environmentally damaging, finite, and expensive fossil fuels to renewable energy resources, such as wind [1,2], solar [3], biomass [4,5], geothermal [6], and hydrogen [7], through technological innovations. Wind energy conversion is one of the most promising renewable energy technologies due to the extensive research that has been ongoing over the last decades to optimize aerodynamic performance of wind turbines [8–10], structural design of wind turbines [11,12], control strategies [13–15], site selection [16,17], and the layout of wind farms [18–21]. The focus of the investigations, however, has been mostly limited to single-rotor wind turbines with three blades as the most popular wind energy conversion technology, and there are only a few studies that have taken into consideration wind turbines with double rotors, either co-rotating or counter-rotating [22–33]. These studies are briefly reviewed here.

According to the Betz's law, the power coefficient of an isolated single-rotor wind turbine cannot exceed $C_{P,max} = 0.59$. This maximum power coefficient $C_{P,max}$ was deduced assuming that: the effects of fluid rotation were negligible, the flow was axial, there was no hub, the rotor had an infinite number of blades with no drag force exerted on them, there was no heat transfer, the flow was incompressible, and finally, the thrust force was distributed uniformly over the rotor. Any deviation from these ideal conditions causes a reduction in the power coefficient. Extending from the Betz's law, and based on similar assumptions, Newman [22] proved that the maximum power coefficient of a dual-rotor wind turbine is $C_{P,max} = 0.64$. Hence, under the above mentioned ideal conditions, a single isolated dual-rotor wind turbine can produce approximately 13% more power in comparison with an isolated single-rotor wind turbine. Jung et al. [23] used the blade element theory to investigate the aerodynamic performance of a single small-scale dual-rotor wind turbine (30 kW). The effect of the wake of the upstream rotor on the downstream rotor was taken into account using the wind tunnel data obtained by Neff and Meroney [34]; the aerodynamic interference between the two rotors, however, was neglected. The best aerodynamic performance was achieved with an upstream rotor half the size of the downstream rotor, located at a distance equal to one-quarter of the diameter of the larger rotor.

Dual-rotor wind turbines have also been studied by researchers at Iowa State University. They conducted wind tunnel experiments under neutral stability conditions to investigate the aeromechanics and wake characteristics of a single isolated dual-rotor wind turbine for both co-rotating and counter-rotating cases [24]. The rotors were the same size and were located at a distance equal

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Nomenclature

c	chord length [m]
D	rotor diameter [m]
F	force [N]
f	Coriolis parameter $[\mathrm{rad}\cdot\mathrm{s}^{-1}]$
l	mixing length [m]
P	power [kW]
p	pressure [Pa]
q	temperature flux $[\mathrm{K}\cdot\mathrm{m}\cdot\mathrm{s}^{-1}]$
r	distance between cell center and blade element [m]
S	strain rate tensor $[\mathrm{s}^{-1}]$
t	time [s]
u	wind speed $[\mathrm{m}\cdot\mathrm{s}^{-1}]$
X	X axis in Cartesian coordinates
Y	Y axis in Cartesian coordinates
Z	Z axis in Cartesian coordinates

Greek letters

Δ	filter width [m]
δ	Kronecker delta
ε	alternating unit tensor
θ	temperature [K]
ν	turbulent viscosity $[\mathrm{m}^2\cdot\mathrm{s}^{-1}]$
ρ	density $[\mathrm{kg}\cdot\mathrm{m}^3]$
τ	stress tensor [Pa]
Φ	site latitude [rad]
ω	Earth rotational speed $[\mathrm{rad}\cdot\mathrm{s}^{-1}]$

Subscripts

T	thrust
P	power
i	index of X direction
j	index of Y direction
k	index of Z direction
ext	external

Acronyms

ALTR	alternate-row
C_P	power coefficient
C_T	thrust coefficient
DRWT	dual-rotor wind turbine
LES	large eddy simulation
PISO	pressure implicit with split operator
Pr	Prandtl number
SOWFA	simulator for wind farm applications
SSR	sub-synchronous resonance
RANS	Reynolds averaged Navier–Stokes

Constants

$\mathrm{C_s}$	Smagorinsky constant
g	gravitaional acceleration

to one-quarter of the rotor diameter from each other. In addition to measuring power output and wind loads, they used particle image velocimetry to quantify the flow characteristics in the near-wake of turbines. Their measurements revealed that the power production performance of the dual-rotor wind turbines and the wind loads acting on them were much higher compared to those of a single-rotor wind turbine. Furthermore, the rotational direction of the rotors was found to have a significant effect on the aeromechanic performance of the dual-rotor wind turbines; the counter-rotating dual-rotor wind turbine was found to harvest more energy than the co-rotating dual-rotor wind turbine. They also studied a unit of two in-line wind turbines where the upstream one had two rotors and the downstream one had one rotor [25]. The secondary rotor of the dual-rotor wind turbine, located immediately upstream of the main rotor, was approximately half the size of the main rotor. The single-rotor wind turbine located downstream of the dual-rotor wind turbine was found to produce more power in comparison with the single-rotor wind turbine located downstream of another single-rotor wind turbine, provided that the distance between downstream and upstream turbines was larger than 4D, where D is the rotor diameter. In a different study, they solved Reynolds Averaged Navier–Stokes (RANS) equations to find an optimal design for a single isolated dual-rotor wind turbine that gives the highest power coefficient C_P at one operating point [26]. Three optimization parameters were taken into account: the rotor diameter, the distance between the two rotors, and the tip-speed ratio. Two two-dimensional parametric sweeps were carried out. First, the secondary rotor size and tip-speed ratio were varied while the distance between two rotors was constant. An optimal diameter of D/4 was found for the secondary rotor, where D was the diameter of the main rotor. Then, the distance between the rotors and the tip-speed ratio of the secondary rotor were varied while holding the secondary rotor diameter at the optimum value (i.e. D/4). The best performance was obtained for a distance of 2D between the two rotors, where D was the diameter of the main rotor. The optimal tip-speed ratio was found to be 6. This optimal design caused the power coefficient of the wind turbine to increase by approximately 7%. They then conducted large eddy simulations under neutral and stable atmospheric conditions to study the effects of atmospheric stability conditions on the performance of the above mentioned optimal design [27].

Shen et al. [28] used the actuator line model along with the EllipSys3D code to simulate flow over a single isolated dual-rotor wind turbine. The EllipSys3D code, developed at the Technical University of Denmark in cooperation with the Department of Wind Energy at Risø National Laboratory, is a finite volume discretization of the incompressible Reynolds averaged Navier–Stokes (RANS) equations in general curvilinear coordinates. The dual-rotor wind turbine was assumed to have two rotors of the same size with a distance varying from 0.05D to 0.4D, where D was the rotor diameter. The mean power coefficient was found to be almost independent of the distance between the rotors in the studied range. The amplitude of the fluctuations of the instantaneous power coefficient, however, was found to significantly decrease with the distance between the rotors.

In addition to the aerodynamic performance, several other aspects of dual-rotor wind turbines, such as design, control and electrical concerns, have been taken into consideration. Farahani et al. [29] evaluated the fault-ride-through capability of dual-rotor wind turbines and single-rotor wind turbines under constant pitch angle and constant speed conditions, and realized that dual-rotor wind turbines introduce higher damping torque to the network in both constant speed and constant pitch angle modes. By using dual-rotor wind turbines, both steady state and transient performance of the wind farm would be enhanced. They also evaluated risk of subsynchronous resonance (SSR) for both single-rotor and dual-rotor wind turbines [30]. They introduced a genetic algorithm for optimizing the dual-rotor system design with the objec-

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