Operation process and response characteristics of the wind turbines under complex terrain using a multi-scale coupling model

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ABSTRACT

A multi-scale coupled model of wind farms simulation combined with mesoscale and micro-scale models is newly developed in the present work. The mesoscale simulation is based on mesoscale wind farm parameterized (WFP) coupling model WFP-WRF, while the micro-scale calculation using large eddy simulation coupling wind turbine control method. Based on the WRF-CFD coupled model, the multi-scale simulations of the flow field and operation characteristics of an onshore wind farm under complex terrain are carried out. The accuracy of wind power output results based on the mesoscale WFP-WRF model and the multi-scale WRF-CFD model is tested on the basis of the wind farm operation data, the results show that compared to the mesoscale WFP-WRF model, the WRF-CFD multi-scale model has obvious advantages in capturing the flow details and improving the simulation precision of the wind farm. Then, the influence of wake interference on the operating characteristics of downstream wind turbines is discussed. Final, this paper considers the three conditions of the wind turbine on the upwind of the slope, the top of the slope and the downwind of the slope, respectively, and explores the influence of the terrain on the flow field around the wind turbine and the operating characteristics of the wind turbine. The multi-scale coupled simulation platform developed in the present work can be used to assist the macro-siting and micro-siting of wind farms and has important engineering application value.

INTRODUCTION

With the rapid development of wind power industry in recent years, the wind resources of flat terrain suitable for the construction of wind farms have been used in succession

(Böhme et al, 2018). Nowadays, wind power developers are increasingly turning their attention to wind resource in complex terrain (Dhunney et al, 2017; Kozmar et al, 2016). Therefore, it is of great significance for the further development of the wind energy industry to develop fine wind resource assessment methods for complex terrain (Carvalho et al, 2013).

Wind resource assessment for complex terrain is difficult to be carried out through wind tunnel experiments, and it is impossible to accomplish the assessment only by means of observation data collected by wind masts (Dhunney et al, 2017). Compared with the former two methods, the numerical simulation method can deal with various terrain and different atmospheric inflow boundary conditions flexibly, and it can obtain complete and continuous wind data in the area to be evaluated (Carvalho et al, 2013; Murali & Rajagopalan, 2017; Wakes et al, 2010). Accordingly, the numerical simulation method plays an important role in the complex terrain wind resource assessment.

At present, there are still some problems to be solved in multi-scale simulation studies on wind farms (Carvalho et al, 2013). One is that the grid resolution of mesoscale simulation is still very rough, and most of the mesoscale simulation studies do not consider the interaction between wind turbines and the atmospheric boundary layer (ABL), therefore, it is difficult to accurately resolve the flow inside the wind field. The second is that the micro-scale wind farm simulation fails to take into account the various control strategies used in the actual operation of wind turbines (Cambron et al, 2016), hence, it is impossible to analyze the correct operating state of each wind turbine in the wind farm.

To make up for the deficiency of existing research, a multi-scale coupled simulation model of wind farms is newly

developed. First, we coupled the wind farm parameterization model in the mesoscale simulation framework, and the interaction mechanism between the wind farm and the atmospheric boundary layer is modeled. Second, in the micro-scale mode, through the parametric modeling of wind turbine torque control and pitch control method, we developed a wind farm CFD calculation framework coupled with a wind turbine control method. Based on the above work, we conducted a multi-scale simulation study on a real onshore wind farm and verified the current model based on the operating parameters of the wind farm. The multi-scale simulation platform developed in this paper can be used for macro-siting and micro-siting of wind farms and has important engineering application value.

METHODOLOGY

Multi-scale models: mesoscale

The model of Weather Research and Forecasting, version 3.7.1, was applied to obtain the initial wind field for the target wind farm (Aitken et al, 2014). The dynamic solver of Advanced Research WRF (ARW) is a state-of-the-art mesoscale model, whose advantage lies in resolving the flow and performance characteristics of the wind farm in a real atmospheric environment.

The vertical coordinate is defined as:

$$\eta = (p_{dh} - p_{dht}) / \mu_d \quad (1)$$

where $\mu_d = p_{dhs} - p_{dht}$ stands for the dry air mass. The flux form variables are:

$$\mathbf{U} = \mu_d \mathbf{u} = (U, V, W), \Omega = \mu_d \omega, \Theta = \mu_d \theta \quad (2)$$

The moist Euler equations in the vertical coordinate are:

$$\partial_t U + (\nabla \cdot \mathbf{U}u) + \mu_d \alpha \partial_x p + (\alpha / \alpha_d) \partial_\eta p \partial_x \phi = F_U \quad (3)$$

$$\partial_t V + (\nabla \cdot \mathbf{U}v) + \mu_d \alpha \partial_y p + (\alpha / \alpha_d) \partial_\eta p \partial_y \phi = F_V \quad (4)$$

$$\partial_t W + (\nabla \cdot \mathbf{U}w) - g[(\alpha / \alpha_d) \partial_\eta p - \mu_d] = F_W \quad (5)$$

$$\partial_t \Theta + (\nabla \cdot \mathbf{U}\theta) = F_\Theta \quad (6)$$

$$\partial_t \mu_d + (\nabla \cdot \mathbf{U}) = 0 \quad (7)$$

$$\partial_t \phi + \mu_d^{-1}[(\mathbf{U} \cdot \nabla \phi) - gW] = 0 \quad (8)$$

$$\partial_t Q_m + (\nabla \cdot \mathbf{U}q_m) = F_{Q_m} \quad (9)$$

The ARW is a fully compressible and non-hydrostatic model, and its mass vertical coordinate is expressed by Eq. (1). Here, μ_d and p_{dh} stand for the dry air mass and the hydrostatic pressure of the dry atmosphere, respectively. p_{dhs} and p_{dht} refer to the values along the surface and top boundaries, respectively. Because $\mu(x, y)$ represents the mass per unit area within the model domain at (x, y) , the flux form variables is written in Eq. (2), in which $\mathbf{u} = (u, v, w)$ represents the covariant velocities in the horizontal and vertical directions; ω represents the contravariant vertical velocity; θ represents the potential temperature. To facilitate the construction of conserved difference scheme and discuss

the energy conversion relationship with atmosphere, the moist Euler equations can be formulated as Eqs. (3)-(9), including the forcing terms arising from model physics (F_U), turbulent mixing (F_V), spherical projections (F_W), and the rotation of Earth (F_Θ). ϕ is the geopotential, $\alpha = \alpha_d(1 + \sum q_i)^{-1}$ is the inverse density, α_d is the inverse density of dry air, and $\sum q_i$ is the sum of mixing ratios. Moreover, $Q_m = \mu_d q_m$, where q_m is equal to one of the mixing ratios. The diagnostic equation for dry inverse density is $\partial_\eta = -\alpha_d \mu_d$ while it for the full pressure is $p = p_0(R_d \theta_m / p_0 \alpha_d)^\gamma$, where p_0 is the reference pressure, R_d is the gas constant for dry air, and γ is the ratio of the heat capacities for dry air.

Multi-scale models: microscale

A large-eddy simulation (LES) solver is used to resolve the filtered incompressible Navier-Stokes equations by means of a pseudo-spectral discretization in the horizontal directions and a second-order finite central differencing scheme in the vertical direction (Medjroubi et al, 2014). The sub-grid scale stress is closed by the Smagorinsky model, and the body force is modeled using the actuator line method (ALM), which is widely used in the previous studies (Eriksson et al, 2015; Mikkelsen et al, 2007; Naderi & Torabi, 2017).

The actuator line method, proposed by Sørensen and Shen (Sorensen & Shen, 2002), is adopted to quantify the turbine-induced forces. Based on the blade element momentum (BEM) theory, the wind turbine blades are described by a set of actuator points along each blade axis. In addition, the blade forces, *i.e.*, the lift and drag forces, can be determined by the design blade parameters including airfoil type, chord, twist, and lift/drag coefficients. The relative speed is a dominant factor determining the magnitude of forces, which is given by:

$$U_{rel} = \sqrt{U_a^2 + (\Omega r + U_t)^2} \quad (10)$$

where Ω represents the rotor speed, U_a represents the axial inflow speed, and U_t represents the relative tangential speed. The vector relationship of the above speeds is determined by the blade pitch angle θ , the inflow angle ϕ , and the angle of attack α .

The body force of each actuator element produced by the wind flow can be calculated by:

$$\mathbf{f} = (L, D) = 1/2 \rho U_{rel}^2 c(C_l \mathbf{e}_L + C_d \mathbf{e}_D) \quad (11)$$

where $\mathbf{e}_L$ and $\mathbf{e}_D$ respectively stand for the unit vectors of lift and drag force. While the effect of flow fields on the rotor is reflected by mapping the force relations. Here, the Gaussian function is utilized to represent the body force projection on the flow field surrounding the actuator elements.

$$\eta_\varepsilon = \frac{1}{\varepsilon^3 \pi^{3/2}} \exp\left[-\left(\frac{r}{\varepsilon}\right)^2\right] \quad (12)$$

where ε is the projection width, and r is the distance from the actuator point to the point where the force is applied.

Thus, the body force for each actuator point of the rotor is expressed as:

$$f(x, y, z, t) = f \otimes \eta_\varepsilon = \sum_{i=1}^N f(x_i, y_i, z_i, t) \frac{1}{\varepsilon^3 \pi^{3/2}} \exp\left[-\left(\frac{r_i}{\varepsilon}\right)^2\right]. \quad (13)$$

where (x_i, y_i, z_i) is the coordinate of the i^{th} actuator point, and N is the total number of actuator points.

In addition to the above-mentioned LES and ALM approaches, the wind turbine control strategies, such as generator-torque control and pitch control, developed and embedded in the microscale model are introduced below.

Generator-torque controller

In order to keep the maximum energy conversion efficiency, the wind turbine has to operate at a constant tip speed ratio (Quallen & Xing, 2016). Therefore, to improve the wind turbine operating efficiency and reduce the load on the wind turbine, the operating state should be timely adjusted according to the local inflow wind conditions. When the inlet wind speed is smaller than the rated wind speed, it is necessary to adjust the generator torque so that the wind turbine can keep a constant tip speed ratio. If the inlet wind speed is larger than the rated speed, it is vital to vary the pitch angle to avoid the wind turbine rotor speed exceeding its rated value. This is the generator-torque control (GTC) strategy.

In this controller, the rotor speed Ω is primarily dominated by the rotor aerodynamic torque and the generator torque, and the rate of rotor speed change can be obtained by:

$$\frac{d\Omega}{dt} = \frac{T_{\text{Aero}} \times \eta_{\text{GB}} - T_{\text{Gen}} \times N_{\text{Gear}}}{I_{\text{Dr}}}. \quad (14)$$

where T_{Aero} is the rotor aerodynamic torque, η_{GB} is the gearbox efficient, T_{Gen} is the generator torque, N_{Gear} is the gearbox ratio between the high-speed shaft and the low-speed shaft, and I_{Dr} in the drivetrain inertia of the low-speed shaft.

The aerodynamic torque is provided by the turbine rotor, and the generator torque is transmitted from the generator via the high-speed shaft. The generator torque is a piecewise function of the generator speed n , which can be determined by the generator speed in five regions (J. Jonkman, 2009), termed as Region 1, Region 1-1/2, Region 2, Region 2-1/2, and Region 3. The wind turbine will operate based on the optimal torque-speed curve when the rotor is working at the optimum tip speed ratio. However, the actual torque-speed curve varies as the generator speed increases. The generator torque in Region 1 is zero when the inflow speed is less than the cut-in wind speed. In the Region 1-1/2, generator torque undergoes a linear transition start-up stage. Then, the generator torque rises along the optimal curve, which is proportional to the square of the generator speed to keep an optimal TSR. In order to limit the tip speed at rated value for reducing the noise of wind turbines, another linear transition Region 2-1/2 should be experienced (Quallen & Xing, 2016). Ultimately, at the stage of Region 3, the speed exceeds the rated value, and the power output keeps constant as a result that the generator torque is inversely proportional to the generator speed.

Blade pitch controller

As mentioned above, in the Region 3, the rotor speed and generator speed will be greater than the rated values if the wind speed is greater than the rated speed (Quallen & Xing, 2016). To control the rotor speed and generator speed at the rated condition, the blade pitch controller is a feasible strategy during the operation of a wind turbine. Thus, the Proportional-Integral pitch controller (PIC) is introduced to the present simulations. The PIC assumes that the adjustment signal of the blade pitch angle is treated as a linear combination of the proportional signal and integral signal for speed deviation. Thus, the blade pitch angle signal $\Delta\theta$ can be obtained by:

$$\Delta\theta = K_P N_{\text{Gear}} \Delta\Omega + K_I \int_0^t N_{\text{Gear}} \Delta\Omega dt. \quad (15)$$

where K_P and K_I are the proportional and integral gains for the PI controller, respectively; and $\Delta\Omega$ is the rotor speed deviation relative to the rated speed. Here, the gains of K_P and K_I are given by:

$$\begin{cases} K_P = \frac{2I_{\text{Dr}}\Omega_0\zeta_\varphi\omega_{\varphi n}}{N_{\text{Gear}}(-\partial P/\partial\theta)} \\ K_I = \frac{I_{\text{Dr}}\Omega_0\omega_{\varphi n}^2}{N_{\text{Gear}}(-\partial P/\partial\theta)} \end{cases}. \quad (16)$$

where Ω_0 stands for the rated rotor speed, ζ_φ stands for the damping ratio, and $\omega_{\varphi n}$ stands for the natural frequency. Moreover, $\partial P/\partial\theta$ represents the sensitivity of aerodynamic power to blade-pitch angle, which can be determined by wind speed, rotor speed, and blade pitch angle.

To simplify the model, it is calculated based on the conditions with rated wind speed, rated rotor speed, and zero-pitch angle, and a dimensionless gain-correction factor $\text{GK}(\theta)$ is introduced by:

$$\text{GK}(\theta) = \frac{1}{1 + \theta/\theta_k}. \quad (17)$$

where θ_k is the corrected blade pitch angle at which the pitch angle sensitivity is two times of the pitch angle in the rated operating condition (Gao et al, 2015; Quallen & Xing, 2016). Ultimately, the exact gains of K_P and K_I varied with the pitch angle can be calculated by:

$$\begin{cases} K_P(\theta) = \frac{2I_{\text{Dr}}\Omega_0\zeta_\varphi\omega_{\varphi n}}{N_{\text{Gear}}\left[-\frac{\partial P}{\partial\theta}(\theta=0)\right]} \text{GK}(\theta) \\ K_I(\theta) = \frac{I_{\text{Dr}}\Omega_0\omega_{\varphi n}^2}{N_{\text{Gear}}\left[-\frac{\partial P}{\partial\theta}(\theta=0)\right]} \text{GK}(\theta) \end{cases}. \quad (18)$$

Furthermore, a novel multiscale numerical model for demonstrating the performance characteristics of the wind turbines in the realistic wind farm on complex terrain was established by a combination of the mesoscale model coupled wind farm parameterization and the microscale model embedded with the control strategies. Among them, a user-defined wind profile obtained from the mesoscale model could provide a more accurate inflow boundary condition for

the microscale simulations. Details of the multiscale simulation were deeply described in the next section.

Multi-scale models procedure

To complicate the multi-scale simulation, three steps should be carried out:

- (a) A preprocessor simulation conducted by the mesoscale model in a relatively coarse resolution;
- (b) Obtaining the fine initial boundary conditions by using linear interpolation based on the grid information in the microscale simulations.
- (c) The LES-ALM in microscale is implemented based on the open-source software, OpenFOAM.

COMPUTATIONAL DETAILS

The study site was an onshore wind farm, termed Muren, located in northeastern Inner Mongolia of China. Fig. 1 illustrates the configuration of the terrain and the target turbines. The field geomorphic characteristics belong to the plateau with medium hills. Specifically, the altitude in the north of the region is higher than that of the south, and the altitude difference of this region is about 100 m. Moreover, the technical parameters of wind turbine were obtained from the manufacturer, including the rated power ($P_{\text{rate}} = 1.5$ MW), rated wind speed ($U_{\text{rate}} = 11$ m/s), rotor diameter ($D = 77$ m), hub height ($h_{\text{hub}} = 70$ m), and the cut-in/out wind speed ($U_{\text{cut-in/out}} = 3$ and 25 m/s).

Figure 1 Schematic diagram of the target wind turbines in the wind farm

In the present WRF model, the National Center for Environmental Prediction Final Analysis (NCEP-FNL) data at 6-hour intervals were used for the model initialization. The MODIS land-cover was classified in the simulation, and the geographical data resolution for the study wind farm was set as modis_30s+30s. A four-dimensional data assimilation system and the grid nudging scheme were used. Three nested domains were used to the horizontal grid and two-way nesting between the domains was adopted. Moreover, the horizontal grid resolution was 200 m for the innermost domain, and 81 levels were set in the vertical direction. The specific WRF model configuration and its validation have been reported in our previous study (Wang et al, 2019).

The simulations in this study were conducted based on the open-source software OpenFOAM. A large-eddy simulation coupled with the actuator line method was used to simulate the wind farm. The grid resolution around the wind turbine is about 2 m. The total number of grids in the entire calculation domain is about 18.54 million. To obtain an

accuracy inflow boundary conditions close to the real atmosphere, the wind speed profile obtained from the mesoscale simulations were interpolated. The average wind speed profiles were fitted using three methods, *e.g.*, the classical exponential fitting and logarithmic fitting, and a cubic polynomial fitting, as shown in Fig. 2. It can be seen that the result obtained by the cubic polynomial fitting was in line with the actual wind profile. Therefore, the distribution of inlet mean wind speed in the vertical direction was determined according to this fitting. In addition, in order to implement an inflow condition with turbulence, a fluctuation velocity was generated by the Kinematic Simulation (KS) method (Fung et al, 1992; Meyer & Eggersdorfer, 2014). Moreover, other boundary conditions are listed in Table 1.

Figure 2 Wind profile for mean inflow

Table 1 Summary of the boundary conditions.

Boundary	Velocity	Pressure
Inlet (South)	user-defined	zeroGradient
Outlet (North)	inletOutlet	fixedValue (0 Pa)
lower (Ground)	fixedValue (0 m/s)	zeroGradient
Upper (Top)	slip	slip
Lateral (West & East)	slip	Slip

The sub-grid scale viscosity was modeled using the Smagorinsky model in LES. The pressure and velocity were solved using the PISO (Pressure-Implicit with Splitting of Operators) algorithm. The Gauss linear scheme was used for spatial discretization and the backward scheme was applied to the time discretization. In the present simulations, each turbine blade was represented by 40 actuator points. Based on CFL (Courant-Friedrichs-Lewy) law (Martinez et al, 2012), the time step was set as 0.025 s. In order to ensure the flow develop fully, the total computation time for each case was 2700 s.

RESULTS AND DISCUSSION

As we all know, due to the random fluctuation of wind speed in nature, particularly for the complex terrain where the wind turbines installed, the wind speed varies at each wind turbine. It is necessary not only to assess the performance characteristics of wind turbines under the quasi-static condition but also the dynamic wind inflow condition.

Therefore, a dynamic inflow profile with sinusoidal fluctuations was designed for this Multiscale-Control model based on the cubic polynomial fitting wind profile.

The dynamic inflow wind profile can be expressed as a function of vertical height z and time t :

$$U_{in}(z, t) = U_{poly}(z) \cdot (c_v + |\sin(\pi t / T)|) \quad (19)$$

where U_{poly} is the cubic polynomial fitting wind speed and z is the vertical height; c_v is the inflow speed correction constant, which is set as 0.3 depending on the cut-in speed of the wind turbines; T is the inflow speed fluctuation period ($T = 300$ s). The end time of this simulation is $4T$, which could obtain a fully developed result. To gain insight into the influence of terrain on the performance characteristics of wind turbines, the flow behavior around the wind turbines at upwind, top, and downwind of the hill, the control process and the response characteristics of these wind turbines will be analyzed comprehensively as below.

Based on the results obtained from the Multiscale-Control model, the control process of wind turbines (*i.e.*, the rotor speed and pitch angle variation, and the driving force rotor/generator torques) located at these three different locations of hills were analyzed. To show the curves clearly, the modeling operating parameters of the last period of simulation under the dynamic inflow condition are presented, as shown in Fig. 3. Moreover, the dynamic inflow wind speed curve at the hub height and the corresponding rated values are also marked.

Figure 3 (a) Rotor speed and pitch angle, and (b) rotor and generator torque for the wind turbines of UWT, TWT, and DWT.

Fig. 3(a) shows the variations of rotor speed and pitch angle with the change of inflow wind speed at the hub height for the three wind turbines, *i.e.*, UWT (WT-8), TWT (WT-12) and DWT (WT-10). Generally, the PIC method begins to work at the $t_{rate-in}$ when the wind speed is greater than the rated value and end at the $t_{rate-out}$ when the wind speed is lower than the rated value. However, it can be seen that the start/end points of PIC are advanced and delayed to some degree due to the effect of terrain. For TWT, as the inflow speed rises the rotor speed increase sharply and reaches the rated rotor speed, which is apparently earlier than UWT and DWT. Then, the rotor speed is limited and slows down slightly until the inflow speed is lower than the rated value. The details of the GTC control results will be discussed subsequently. After $t_{rate-out}$ the rotor speed is reduced sharply and the PIC stops working (the pitch angle plummeted to zero). Meanwhile, it also can be seen that the rotor speed of TWT diminishes more slowly than UWT and DWT. It concludes that the performance property of the wind turbines located upwind or downwind is weakened because of the obstacle turbulence caused by the hill. Contrarily, the wind turbines installed at the top of the hill make full use of the acceleration effect, prolong the optimal operation time and promote the operating characteristics of the wind turbines.

In fact, the rotor speed is controlled by the aerodynamic torque generated by the rotor and the generator torque produced by the shaft. The variations of aerodynamic torque and generator torque with the change of inflow wind speed at the hub height for these three wind turbines are depicted in Fig. 3(b). Generally, at the first stage in GTC control, the torques increase sharply as the inflow speed increases and reach the maximum value before the $t_{rate-in}$. While the magnitude of the rotor aerodynamic torque is greater than the generator torque, as presented in Eq. (14), thus the rate of rotor speed change is positive. Then, when the wind speed is greater than the rated value, both of the two torques quickly drop to be nearly equal and fluctuate within a range until the wind speed lower than the rated value. Subsequently, after the wind speed is lower than the rated speed, the aerodynamic torque, and the generator torque decrease. The latter is larger than the former, resulting in the reduction of the rotor speed. In addition, the time points of GTC for different wind turbines are various.

Furthermore, similar to the variations of the control processing parameters, the wind turbine response of outputs performance are various. Fig. 4(a) shows the rotor axial force for UWT (WT-8), TWT (WT-12) and DWT (WT-10). It is observed that the rotor forces and generator power of the wind turbines installed at the different locations of the hill are various. For the rotor axial force, when the wind speed is lower than the rated value, T_a for TWT has the largest magnitude, UWT has a medium value and DWT has the lowest value. Then, when wind speed is greater than the rated value, the GTC strategy is worked. As a result, T_a drops sharply for the three wind turbines, and the magnitude of T_a for TWT is the lowest, however, this values for UWT and DWT are approximately equal and both of them are larger than the TWT.

Fig. 4(b) presents the generator power for three wind turbines. It can be seen that the wind turbine installed at the top of the hill can produce more power during one simulated period. While the power output for the wind turbine located at the upwind or downwind of the hill will slightly diminish compared with the designed power value. Indeed, the fundamental reason for these is that the special wind field properties at the different locations of the hill, *i.e.*, the speed-up effect at the top of the hill, the blocking effect at the upwind of the hill and the vortex cavity generation with high turbulence at the downwind of the hill (Chandel et al, 2014). Therefore, the output capability of wind turbines running downwind of the hillside will be weakened.

Figure 4 (a) Rotor axial force, and (b) generator power for the three wind turbines.

CONCLUSIONS

On the basis of the WRF-CFD model coupled with mesoscale and micro-scale, the multi-scale simulations of the flow field and operation characteristics of an onshore wind farm under complex terrain are carried out. The accuracy of wind power output results based on the mesoscale WFP-WRF model and the multi-scale WRF-CFD model is tested on the basis of the wind farm operation data, the results show that compared to the mesoscale WFP-WRF model, the WRF-CFD multi-scale model has obvious advantages in capturing the flow details and improving the simulation precision of the wind farm. Then, the influence of wake interference on the operating characteristics of downstream wind turbines is discussed. Final, this paper considers the three conditions of the wind turbine on the upwind of the slope, the top of the slope and the downwind of the slope, respectively, and

explores the influence of the terrain on the flow field around the wind turbine and the operating characteristics of the wind turbine. The flow behaviors, control process and response characteristics for wind turbines around three typical installation locations in the realistic wind farm on hills, *i.e.*, upwind-hill-mounted wind turbine, top-hill-mounted wind turbine, and downwind-hill-mounted wind turbine, were comprehensively investigated. Due to the influence of the hill, the flowing nature over the hill's top presented an acceleration effect while the speed deficit and turbulence enhancement appeared at the upwind or downwind of the hill. As a result, about 9.8% optimal operation time is prolonged for the wind turbine installed at the top of the hill and about 1.8% and 5.3% optimal operation time are contracted for the wind turbines installed at the upwind and downwind of the hill. Thus, this model could provide an effective and accurate way to assess the wind power utilization on the complex terrain.

The research in this paper has developed a multi-scale coupled calculation platform for the simulation of the flow and operation characteristics of wind farms. It can be used to assist the macro-siting and micro-siting of wind farms and has important engineering application value.

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