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Wind Farm Inflow Wind Simulation based on Mesoscale and Microscale Coupling

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Abstract. Inflow wind simulation is a critical issue that dominates the wind farm design regarding the actual wind environment. Different from traditional real measurement based wind simulation, this paper proposed a mesoscale and microscale coupling strategy, which applies the forecasting information from WRF model to the LES model based SOWFA. Firstly, an offline coupling strategy is implemented with the modular software interface between WRF and SOWFA. The wind speed, potential temperature and pressure data are converted from Geographic Coordinate to Cartesian coordinate that is a readable format to SOWFA. Then, the simulation domain is selected in daytime for neutral ABL condition at a $1km \times 1km$ region where the wind information from WRF is interpolated and averaged at center point with $100m$ height. Time-series ABL conditions are extracted from center point and force the SOWFA internal solver to simulate the same environment with predictive data. The mesoscale lacked information, turbulence, is generated by periodically running precursor with the surface roughness and boundary conditions. Finally, the comparison between WRF exacted data and SOWFA output verifies the coupling strategy. The result shows that the mesoscale and microscale coupling has high fidelity and accuracy simulation at stable ABL conditions and slow-changing wind environments. This work provides a low cost and reliable data source which allows the inflow wind simulation to have the predictive ability for actual wind.

1. Introduction

Wind energy becomes one of the most important power sources under the background of world-wise carbon neutral policy because of its environmentally friendly factors. A general goal in this field is to harvest more energy assisted by a accurate wind farm simulation. As the input data for the wind energy system, the inflow wind plays a key role in a realistic wind farm simulation including wind evolution, mechanical control, and power calculation, which are driven by the inflow wind. For the current inflow wind reconstruction method, the critical issue is the disconnection between the atmospheric boundary layer (ABL) characteristics in the actual environment and the simulated wind data applied for the system design[1]. There are two objectives for the state of art inflow wind simulation.

Firstly, the simulated inflow wind should have a strong correlation with the real wind. In the traditional simulation, the speed and direction of the coming wind are usually set as a step or sine signal manually. However, the more complex information and quickly changing conditions in the true wind are ignored. In this case, the system design probability doesn't satisfy the real operating environment.

Secondly, the forecasting capability for the inflow wind is also required. Compared with the steady wind data, a long term and dynamic inflow wind information ahead of a wind farm takes more advantages in the simulation. It means that the inflow wind needs to contain a time series of wind information namely the wind prediction. The time gap provided by the wind prediction enables the farm controller to have sufficient preparation against the fast-changing condition.

The Weather Research and Forecasting (WRF) is a mesoscale atmospheric prediction system with the scale from thousands of kilometres to hundreds of meters[2, 3]. It provides the reliable ABL prediction than builds the nesting with the microscale simulation applied on the OpenFOAM based open-source Simulator fOr Wind Farm Applications (SOWFA) platform[4].

To apply the ABL data of WRF to the wind farm simulation on SOWFA, the gap between the mesoscale and microscale simulation should be considered, not only the nesting of model methodologies but also the coupling of simulation platforms[5]. There are two coupling strategies for inflow wind to access the microscale simulation from the mesoscale model[6].

First, the WRF has an internal coupling model so-called WRF-LES, in which the mesh refinement, simulation time step matching, and scale-appropriate are realised online by the physics suite[7, 8]. Both lateral boundary conditions and internal forcing terms in the ABL can be read from the WRF-LES model. However, the LES configuration of inflow wind should be applied on the wind farm simulation (SOWFA), where it lacks a software interface between WRF-LES and SOWFA.

The second method applies an offline modular interface that extracts the ABL data from the WRF model to drive the LES model. The ABL is fully reconstructed with parameter set-up and internal solvers on the SOWFA. Both simulation strategies are verified by the Mesoscale-Microscale Coupling (MMC) project with a variety of measurement data at a certain site[9]. The result shows that the WRF-LES model, offline method, and online method all have an accuracy performance with different application requirements.

Turbulence generation is a challenge during coupling since the WRF model does not resolve microscale information with the large mesh scale and long time step[10]. The external turbulence tools, such as Turbsim and Mann model[11], can be utilized by the information of surface roughness and boundary flow to generate certain turbulence. An alternative method is realised by the precursor on SOWFA, in which the flow runs periodically with a certain surface roughness to reach the quasi-equilibrium.

In this paper, the offline coupling strategy is proposed based on a WRF-SOWFA interface to convert the data format. The turbulence is derived by a periodical running precursor on SOWFA. The simulated inflow wind is verified by the comparison with WRF output.

2. Methodology

2.1. The Weather Research and Forecasting model

The Weather Research and Forecasting (WRF) model attributes to the widely-used mesoscale prediction as the reliable result and variety of weather information[12]. Compared with the current Doppler LIDAR measurement, the WRF model outputs fulfil requirements to choose as the simulated inflow wind for advantages that it has a longer forecast time and more information in concerned ABL space. Besides, there is almost no device expended to run a WRF model except the computational cost under the condition that the global weather data is usually published to the public and free to quote as the input of the WRF model.

In this paper, a finished WRF simulation provides the output file that contains the weather forecasting at mainly Europe from 2015-06-25-12:00:00 to 2015-07-07-12:00:00, shown in Figure 1. The microscale simulation concerned information is written in a .nc format file with multi-dimension data, the examples of variables are shown in Table 1.

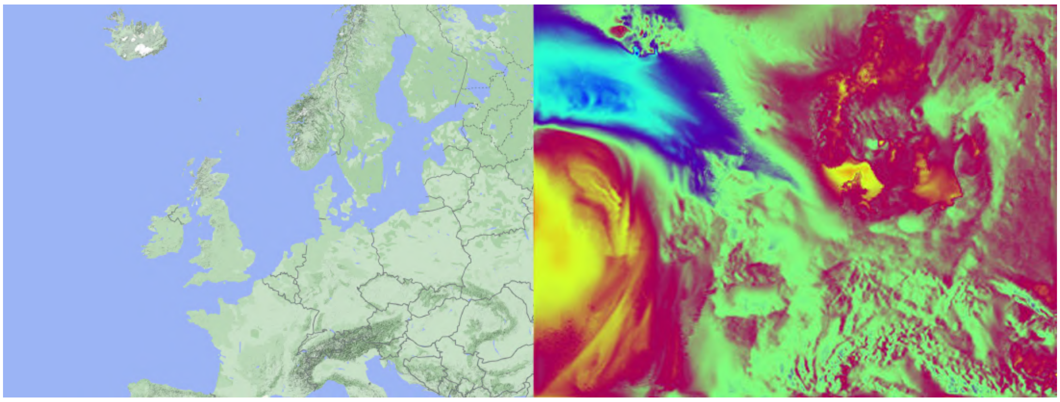

Figure 1. WRF model domain and wind speed at 10m height

Table 1. Variable examples from WRF output

Variables	Value	Dimension
Latitude	41.447°∼68.0737°	1D
Longitude	-35.0345°∼41.0345°	1D
Time	2015-06-08-12:00:00∼2015-06-25-12:00:00	1D
U10	–	3D
U	–	4D
T	–	4D

2.2. Large Eddy Simulation on SOWFA

Large Eddy Simulation (LES) model is a high fidelity Computational Fluid Dynamics (CFD) model applied to the wind farm simulation on the OpenFOAM solver based SOWFA platform. Many numerical tools on SOWFA are developed for specific wind energy areas, such as actuator disk, actuator line, and actuator line, which could couple with OpenFAST for controller design purpose[13, 14]. As an open-source platform, the ABL environment on SOWFA could be built by the parameters configuration regarding the inflow wind characteristics from WRF.

2.3. Coupling Interface

Since WRF supplied WRF-LES model cannot be applied on SOWFA directly, the offline strategy with a modular interface is more appropriate for the mesoscale and microscale coupling in wind energy simulation. The state of art offline coupling has two kinds of interface, internal and external[15].

The first method focus on the model level that refines the mesh of WRF to the same scale with LES. A SOWFA readable format forcing term is converted and derived by the tendency, equations of motion, and changing rate of ABL, which are extracted from WRF output. Finally, the inflow wind is generated by the forcing term driving surface flow of the microscale domain on the SOWFA.

The other method, external coupling on the software level relys on an interface between WRF and SOWFA. The information from WRF is interpolated around the interest region because the mesh of WRF is too large to fit a wind farm domain. Then, choose the average of a concerned area or one grid column which can represent inflow wind characteristics as the initial boundary conditions of ABL, generally at center of wind farm with the height of wind turbine, shown in Figure 2. This method runs most of work on SOWFA and has a low computational cost. In this paper, the external strategy is selected for the fast calculation and flexible application in further wind energy simulation.

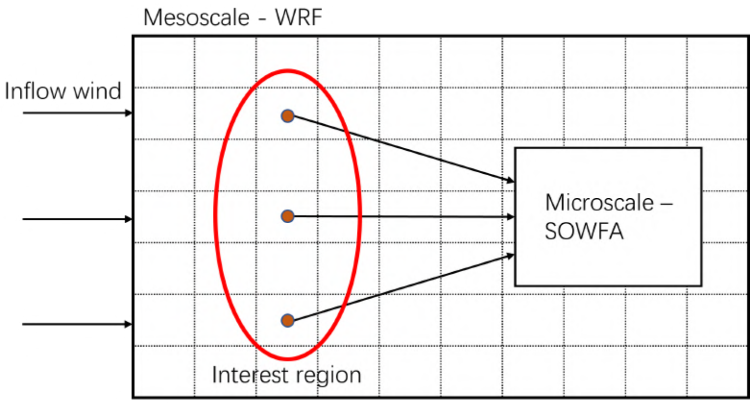

Figure 2. The interface between WRF and SOWFA

2.4. Turbulence Generation

An important characteristic in ABL for wind energy is turbulence information that is not involved in the WRF simulation because of its large mesh scale and long time step. The turbulence is mainly decided by the surface roughness and boundary conditions. Mesoscale and microscale coupling needs another tool to fill this gap based on the limited information from WRF output. Generally, there are two strategies to generate turbulence[16].

The first strategy is implemented with an external turbulence tool that drives the turbulence by WRF based terrain and flow information, for example, the Mann model and Turbsim tool. The disadvantage is obviously at WRF-SOWFA coupling, the external method requires an extra interface for two softwares.

SOWFA has an internal method named precursor in which the turbulence is generated by periodically running with initial conditions and terrain information[17]. LES model is also applied to the precursor simulation for a high fidelity result. At around 20000 s, the quasi-equilibrium is reached to simulate the full evolution of the real wind. A variety of conditions in WRF has the possibility to import to the SOWFA to spin up the turbulence in the precursor since there is no gap from the final wind farm simulation platform.

3. Simulation

3.1. WRF Simulation With A Reduced size

In this paper, a $1\times1km$ domain nearby the seaside of Netherlands and Germany is selected for mesoscale and microscale coupling. To obtain a more accurate forecasting result, we reduce the size of WRF according to the specific SOWFA domain, details are shown in the Figure 4 and Table 2.

Table 2. Information of the size reduced WRF domain

Variables	Value
Latitude	52.7887∼55.0587°
Longitude	4.75916∼8.61819°
Time	2015-06-25-12:00:00∼2015-06-27-12:00:00

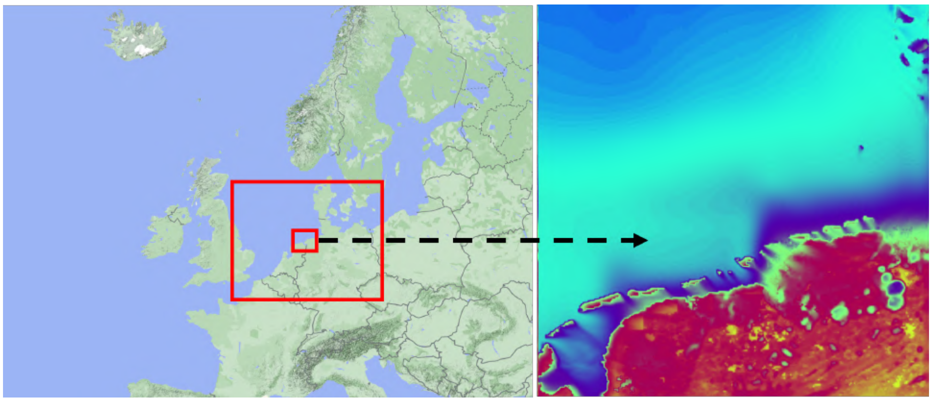

Figure 3. Size reduced WRF domain and temperature at $2m$ height

3.2. Interface of WRF-SOWFA

An open-source interface tool based on SOWFA, named WRF extraction, builds the data format conversion from .nc file of WRF to the SOWFA readable file. Firstly, the desired mesh scale for six boundaries of the domain is built by the list of points with latitude, longitude and elevation information, which come from the Cartesian coordinates. These coordinate data are written in _bc.dat format that helps the WRF extraction tool to automatically orientate the location and extract the information from the WRF output file. The wind speed vector(U), temperature(T) and pressure(p_rgh) are interpolated in the output file following the mesh set in a time series. There are two controlled inputs, start date and offset, import result with different forecasting time of WRF and align the SOWFA simulation with a real-time.

In this simulation, a $1{\times}1km$ domain is selected as the interest region with center point at 53°30′N, 7°30′E. The wind speed vector, temperature and pressure are extracted by WRF extraction from 2015-06-25-12:00:00∼2015-06-07-12:00:00. Regarding the common turbine height, we choose the centre point with $100height$ of the interest region as the information source.

3.3. Configuration for the wind speed and direction

A $1km \times 1km \times 1km$ grid is generated with 200 cells at every direction of Cartesian coordinates. The velocity U, temperature T and pressure P are extracted from the WRF extraction tool to feed the Dirichlet condition of SOWFA.

An LES based ABL solver in SOWFA deals with the initial conditions to run a precursor based on the wind speed and direction extracted from WRF. The time step is set to $0.5s$, initial wind speed and temperature are set to $4m/s$ and $291K$ respectively at $100m$ height. The inflow wind directions is changed to cyclic which means that the inflow is run periodically, hence, precursor method. After $20000s$, the precursor reaches the quasi-equilibrium. Then, the ABL properties are edited regarding the converted time-series data from WRF output.

4. Result

To specify the simulation time and domain location, Figure 4 is read from WRF directly with the wind speed map and potential temperature map respectively at 2015-06-25-21:00:00 with the turbine height. The simulated wind domain is set closed to the seaside to get a flat terrain and reduce the influence from human activity.

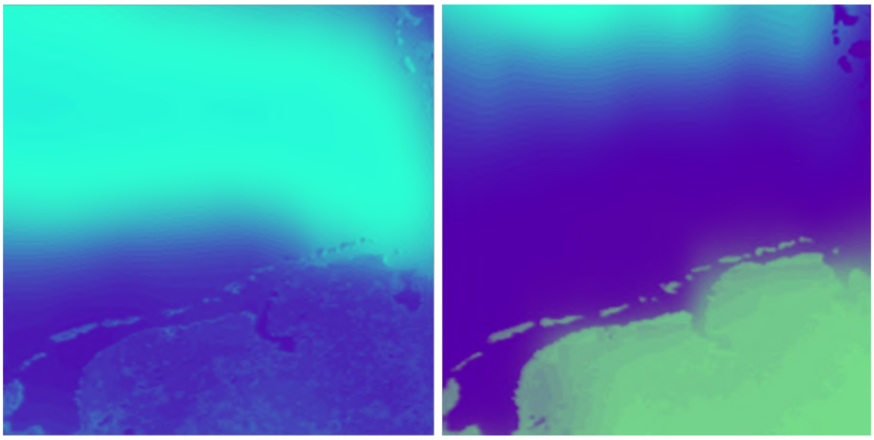

Figure 4. Wind speed (left) and potential temperature (right) from WRF

In this paper, the neutral ABL condition is proposed to test the Mesoscale and Microscale coupling. The wind speed at turbine height is shown in Figure 5. A NREL 5MW turbine is applied for wind farm simulation which needs minimum 8m/s wind speed to generate the power. The grey shadow in Figure 5 shows the wind information during $2800min$∼2850min$after2015-06-25-12:00:00wheresatisfiesboththeneutralABLconditionandwindspeedabove8m/s$.

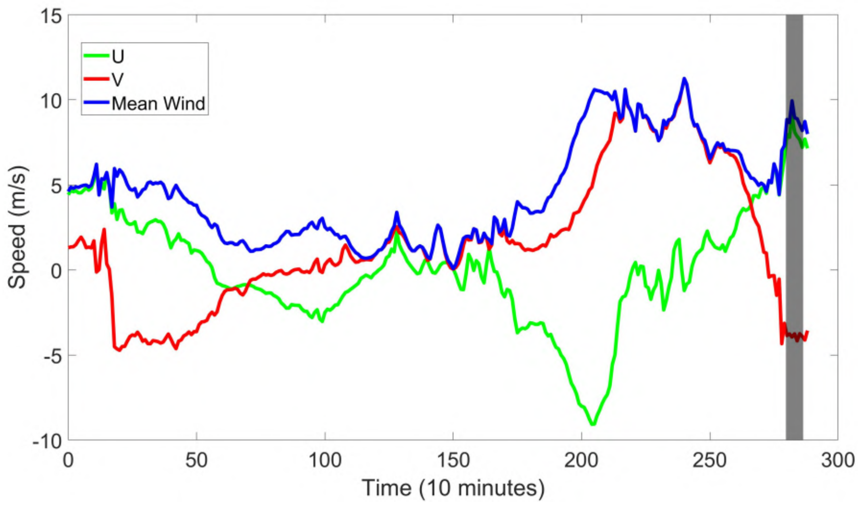

Figure 5. Wind speed from WRF, grey shadow shows simulated neutral condition

Based on the WRF simulation output, the LES model in SOWFA sets 0.002 as surface roughness for turbulence generation because the coming wind comes from the sea where has a small surface roughness. After 20000s periodically running with initial boundary conditions, the

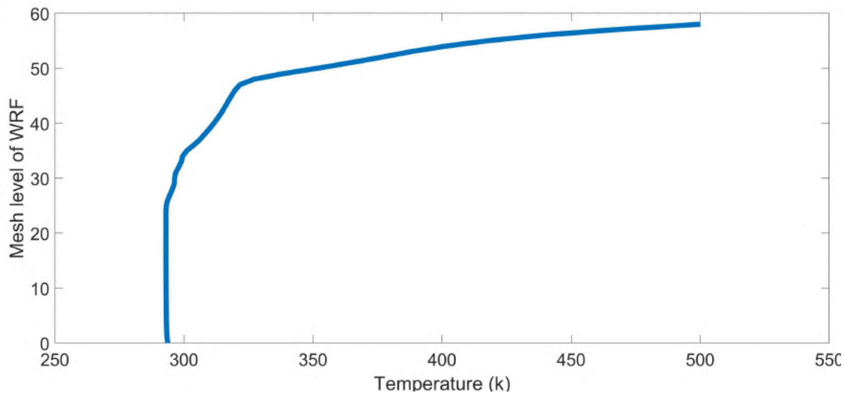

Figure 6. Potential temperature at 280 minutes from WRF

ABL solver of precursor starts to force the flow regarding the interface data until 23000s. In this 50min, the inflow wind and turbulence are simulated and merged, a horizon instantaneous wind speed of SOWFA output including turbulence at 90m height is shown in the Figure 7.

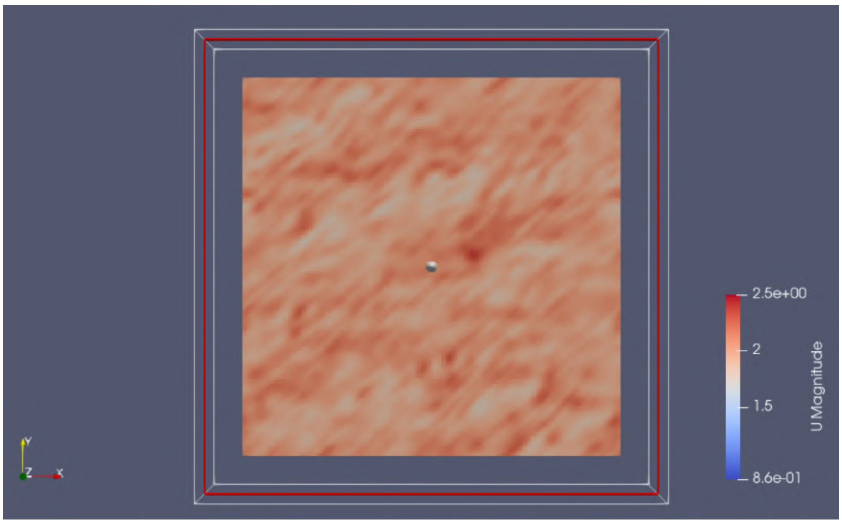

Figure 7. Instantaneous wind speed with turbulence at 100m height from SOWFA

In the SOWFA simulation, a virtual probe is located at center of the domain to record the data. Figure 8 illustrates the comparison between interface data from WRF (red line) and recorded data at the probe from SOWFA (blue line), two sub-picture shows mean wind speed and wind direction respectively. Results validated that the mean value of mesoscale and microscale coupling outputs has a fast and accuracy following WRF data. The oscillation around mean value show the microscale wind information, turbulence and sheer, which is lacked in the WRF and fulfilled by the SOWFA precursor.

For the vertical profile, the average mean wind speed at different height are recorded and compared with the WRF output in Figure 9. The vertical profile shows that the Mesoscale and Microscale coupling not only follows the wind information at wind turbine height but also can provide a reliable vertical wind environment.

At last, a NREL 5MW wind turbine is applied in the wind environment based on the proposed coupling strategy on SOWFA. The yaw controller of turbine ensures that the blade plane keeps

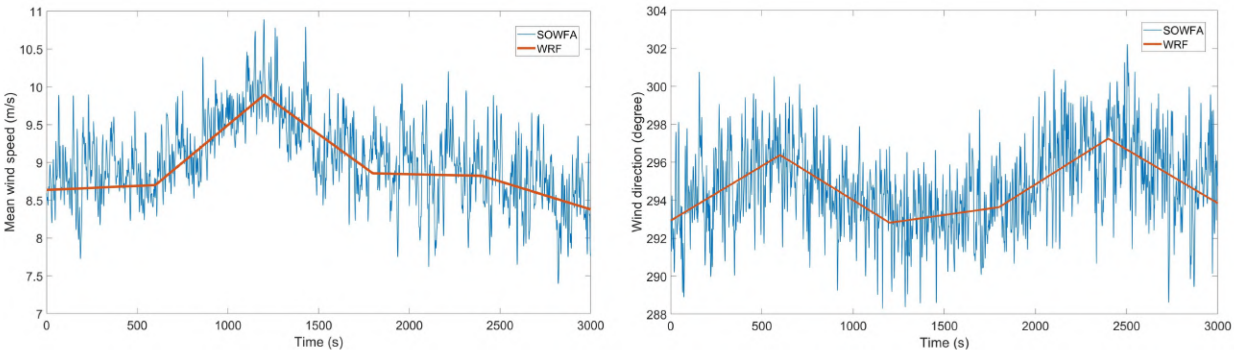

Figure 8. Results comparison between WRF and SOWFA at wind turbine height, mean wind speed (left) and wind direction (right)

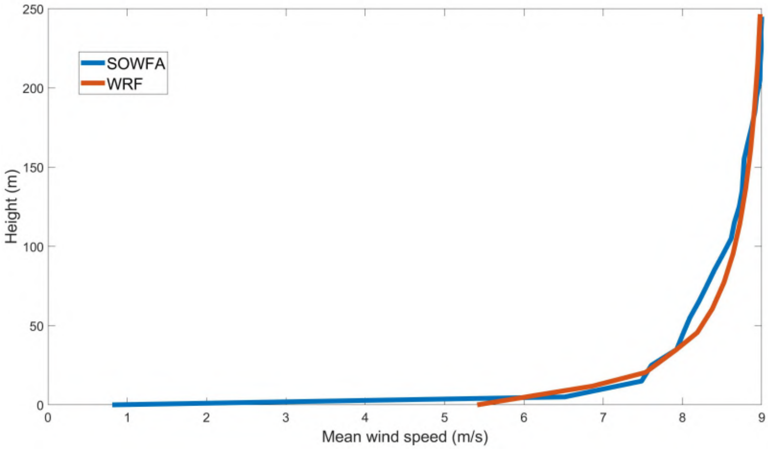

Figure 9. Vertical wind speed comparison between WRF and SOWFA

facing the wind direction. Because the wind speed in this simulation is smaller than rated wind speed of turbine, $12m/s$, there is only torque controller is called but no pitch control. The Figure 10 shows the power generation of turbine, in which the power follows the wind speed in the left of Figure 8 and reaches the peak, $5MW$ rated power, after $1200s$.

5. Conclusion

In this paper, an offline coupling approach is applied to build the modular interface between mesoscale and microscale. For wind energy inflow wind simulation purposes, the coupling should work not only between WRF and LES model but also different simulation software. Based on the SOWFA internal tool, the WRF output data is converted from .nc format to the SOWFA readable format. The wind speed vector, potential temperature and pressure are extracted with the transform from Geographic Coordinate to Cartesian coordinate.

The size of WRF output is reduced regarding the $1km \times 1km$ interest region where the information is averaged and interpolated around the center point. The precursor model generates the inflow wind as well as turbulence that depends on the boundary condition and surface roughness from WRF output. The ABL solver in SOWFA allows periodically simulation following the interface data. Finally, the comparison between WRF exacted data and SOWFA output verifies the accuracy of mesoscale and microscale coupling.

The simulation result shows that the proposed coupling strategy builds the bridge for data

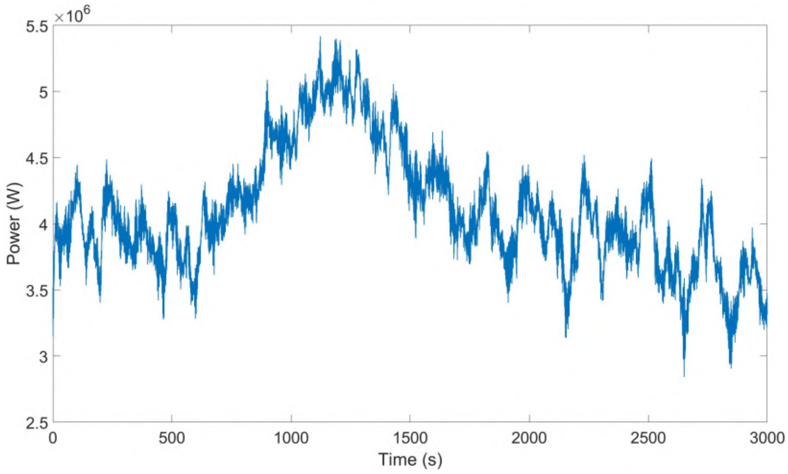

Figure 10. Power generation from a NREL 5MW turbine

conversion and transformation. The inflow wind and turbulence are generated by the data forcing from WRF forecasting, specific under the stable ABL condition and slowly changing wind environment. The mesoscale and microscale coupling provides more possibilities for wind farm design that relies on the inflow wind simulation. Compared with the real measurement, the WRF forecasting has a low cost and variety of information which guarantees the fidelity of the simulation. In further work, the simulation result will be verified with the real measurement data to demonstrate the accuracy at different ABL conditional.

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