Equivalent modeling of wind energy conversion considering overall effect of pitch angle controllers in wind farm

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HIGHLIGHTS

• A transfer function represents the wind energy conversion process with spatial effects.
• A compensation wind speed represents the overall effect of all pitch angle controllers.
• Simplest way to build equivalent model of complete wind energy conversion process.
• Proposed model is identified and validated by measurements from an actual wind farm.
• Example of using proposed model to convert forecasted wind speed into output power.

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ABSTRACT

The correct electric power fluctuation process of a wind farm is essential for the operation and studying of the power grid integrated with wind power. A complete wind energy conversion model, that should take both the spatial effects and the overall effect of all the pitch angle controllers into account, is required to convert the wind fluctuation into the electric power fluctuation. Although some equivalent models have been proposed in previous studies, there is no simple solution for equivalently modeling the non-synchronous actions of the pitch angle controllers in individual wind turbine generators. This study found the relationship between the overall effect of all the pitch angle controllers and the spatial effects of the wind farm and presented a theoretical derivation of the frequency-domain equivalent modeling method. The proposed modeling method is the simplest way to obtain the equivalent model of the complete wind energy conversion process of a wind farm with consideration of all the spatial effects and the overall effects of all the pitch angle controllers. The only input signal of the proposed equivalent model is the speed of the wind before entering the wind farm, which is called the “original incoming wind speed”. Using this compensation wind speed, a compensation power with negative values can be obtained to represent the total reduced power caused by the pitch angle controllers in individual wind turbine generators. A frequency-domain equivalent model has been identified and validated by field measurements of an actual wind farm. The normalized root-mean-squared error of the model is less than 8% over the entire wind process, and the maximum

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error of the power ramp rate in 10 min is less than 5 MW. Finally, an example is provided to demonstrate the online use of the proposed model to convert the forecasted wind speed into output power of a wind farm in ultra-short-term wind power forecast.

### Nomenclature

#### Abbreviations

- CFEM: complete frequency-domain equivalent model
- CWS: compensation wind speed
- DFIG: doubly-fed induction generator
- EPV: error of peak value of output power
- EPRR-1: maximum error of power ramp rate in 1 min
- EPV: error of peak value of output power
- EPRR-10: maximum error of power ramp rate in 10 min
- FEM: frequency-domain equivalent model, includes wind energy conversion process and all spatial effects of wind farm
- MPPT: maximum power point tracking
- NMAE: normalized mean absolute error
- NRMSE: normalized root-mean-squared error
- OIWS: original incoming wind speed, represents speed of wind before entering a wind farm
- PAC(s): pitch angle controller(s)
- WTG(s): wind turbine generator(s)

#### Indices

- \( n \): index of WTG

#### Parameters

- \( C_{PMax} \): maximum value of power coefficient
- \( m \): time range of wind speed forecast
- \( M_0 \): wind starting moment
- \( M_i \): wind speed forecast moments
- \( N \): total number of WTGs

### Variables

- \( P_N \): rated power of WTG
- \( R \): radius of wind turbine
- \( v_N \): rated wind speed of WTG
- \( \rho \): air density
- \( D \): compensation factor to calculate CWS of \( v_0(t) \)
- \( D_h \): wind speed reduction of \( v_0(t) \) compared to \( v_0(t) \)
- \( H(\omega) \): frequency response function of wind energy conversion process and spatial effects in a wind farm
- \( H(\tau) \): discrete-time transfer function of \( H(\omega) \)
- \( P_{el} \): output power of single WTG obtained from \( v_0(t) \) without considering PAC
- \( P_{el} \): output power obtained from \( v_0(t) \) without considering PAC
- \( P_{el} \): compensation power obtained from \( v_n(t) \), represents effect of PAC
- \( P_{el} \): total output of wind farm
- \( P_{el} \): sum of output power of all WTGs, without considering PACs
- \( P_{el} \): compensation power of entire wind farm, represents overall effect of all PACs
- \( P_{el} \): output power of wind farm starting from \( M_i \) produced by wind speed from \( M_0 \) to \( M_i \)
- \( P_{el} \): output power of wind farm from \( M_i \) to \( m \) hours in future, calculated from forecasted wind speed
- \( t_d \): time lag
- \( T_{d} \): total time lag of \( v_0(t) \) relative to \( v_0(t) \)
- \( v_0(t) \): OIWS
- \( v_0'(t) \): CWS of OIWS
- \( v(t) \): wind speed of first WTG along wind direction, can be used as \( v_0(t) \)
- \( v_0(t) \): wind speed of \( n \)-th WTG
- \( v_n(t) \): CWS of \( v_0(t) \)

### 1. Introduction

Getting the correct fluctuation characteristic of the wind power is essential for the dispatching, control, and electric market of the power grids with high wind power penetration [1–4]. Power fluctuations at wind farms are caused by the incoming wind. There are usually two methods to get the wind speed fluctuation in different time scales. One method is using the wind speed models, such as the four-component composite model [5], mean value and turbulence composite model [6], stochastic differential equations based continuous wind speed model [7], and the Weibull distribution based model [8,9]; the other method is through the wind speed forecast [10–14]. However, a large wind farm may comprise hundreds of wind turbine generators (WTGs) and cover a great area. The spatial effects of this will lead to significant differences between the fluctuation characteristic of the incoming wind and that of the output power, especially in a small time scale [15]. Therefore, an appropriate wind energy conversion model is important to obtain the correct electric power fluctuation characteristics of a wind farm.

To obtain a complete wind energy conversion model, the spatial effects on a wind farm should be taken into account. Among the spatial effects, the wake effect [16,17] represents the decrease in the wind speed in the wind direction, the wind shear [18–20] represents the wind speed change caused by undulating terrain, the tower shadow [19,20] represents the airflow disturbance caused by the WTG tower, and the time-lag effect [21,22] represents the time postponement of the wind moving over a certain distance. The spatial effects could also lead to non-synchronous actions of the pitch angle controllers (PACs) in individual WTGs when the wind fluctuates over the rated wind speed of the WTG. However, to construct a detailed time-domain model to represent both the spatial distribution of the WTGs, and the ground environment of the wind farm, is a highly complex task because of the great number of parameters required; parameters are difficult to obtain accurately and comprehensively [23]. Even if all the required parameters are obtained, the detailed model will be too complex. Therefore, building an equivalent model of the wind energy conversion process is more feasible and practical.

Among the existing equivalent models, the equivalent power curve of the wind farm is a widely used time-domain equivalent model for converting the forecasted wind speed into electric power [24–28]. The international standard IEC 61400-12-1 gives a procedure for obtaining the power curve from field measurements. The 10-min average wind speed data are typically used, and a long term data accumulation is required [28–30]. When the equivalent power curve is used for a wind
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