SIMPLIFICATION OF ATMOSPHERIC MODELS FOR REAL-TIME WIND FORECAST

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Abstract: In wind energy industry, it is well known that real-time wind forecast can improve the performance of wind turbines if the prediction information is well used to compensate the uncertainty of the wind. Unfortunately, neither model nor method is available to give a real-time forecast of wind so far. This paper proposed a real-time wind forecast model by simplifying existing weather forecast model, MM5. Details on model simplification, forecast error correction as well as other issues like boundary conditions and simulations are also discussed.

1 INTRODUCTION

Owing to increasing concern over the global environment, there is much interest throughout the world in renewable energy, of which one of the most promising is wind power due to its mature technology, low cost and less environmental impact. Unlike the normal electrical power generation using generated water steam with certain temperature and pressure, wind power utilizes natural but uncertain wind. The wind uncertainty is the root cause for most of the issues in wind power systems, such as nonlinearity, coupling, interaction, and so on. Therefore, it would be much helpful to improve the performance of wind turbines if we could predict the wind and take actions in advance. It would be better if the prediction is real-time since wind is varying all the time.

A natural thought for wind prediction is to make use of weather forecasting models, which has been developed since 1970s and now achieves good prediction for wind, temperature, pressure, moisture, and other weather conditions. Actually in wind power prediction, weather forecasting model has already been applied, see (Landberg, 1999; Joensen et al., 1999; Kazuhito et al., 2006) and references there in, but none of them can give real-time predictions. To the best of our knowledge, not much work has been done yet so far in the real-time wind forecast for wind turbines. This is because:

1. Weather forecasting model is developed for a long-term and large scale forecast, which is not suitable for wind prediction in wind energy industry where only a short-term and small scale forecast is only required;
2. Due to model complexity, the highest temporal resolution of current weather forecasting model is hourly, which is hardly used for real-time prediction.
3. Weather forecasting model lacks of the scheme of correcting prediction error, which is much needed in wind prediction for wind energy industry, especially for real-time forecast.

This paper aims to find a suitable forecasting model for real-time wind prediction. Based on the Fifth-Generation NCAR/Penn State Mesoscale model (MM5) for weather forecast, all possible methods of simplification are discussed to achieve the real-time forecast. Ideas of Kalman filter used to correct the forecast error are also addressed as well as issues on boundary conditions and simulations.

2 MM5 FORECASTING MODEL

MM5 forecasting model is the latest in a series developed from a mesoscale model used by Anthes at Penn State in the early 1970s that was later documented by (Anthes and Warner, 1978). Since that time, it has undergone many changes designed to

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broaden its applications, including (i) a multiple-nest capability; (ii) nonhydrostatic dynamics; (iii) a four-dimensional data assimilation (Newtonian nudging) capability; (iv) increased number of physics options; and (v) portability to a wider range of computer platforms.

In terms of terrain following coordinates (x, y, σ), the partial differential equations for the nonhydrostatic model's basic variables excluding moisture are:

Pressure

$$\frac{\partial p'}{\partial t} - \rho_0 g w + \gamma p \nabla\cdot\mathbf{V} = \mathbf{V}\cdot\nabla p' + \frac{\gamma p}{T}\left(\frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0}D_\theta\right), \tag{1}$$

Momentum (x-component)

$$\begin{aligned}\frac{\partial u}{\partial t} + \frac{m}{\rho}\left(\frac{\partial p'}{\partial x} - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial x}\frac{\partial p'}{\partial \sigma}\right) &= -\mathbf{V}\cdot\nabla u \\ +v\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right) &- ew\cos\alpha - \frac{uw}{r} + D_u,\end{aligned} \tag{2}$$

Momentum (y-component)

$$\begin{aligned}\frac{\partial v}{\partial t} + \frac{m}{\rho}\left(\frac{\partial p'}{\partial y} - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial y}\frac{\partial p'}{\partial \sigma}\right) &= -\mathbf{V}\cdot\nabla v \\ -u\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right) &+ ew\sin\alpha - \frac{vw}{r} + D_v,\end{aligned} \tag{3}$$

Momentum (z-component)

$$\begin{aligned}\frac{\partial w}{\partial t} + \frac{\rho_0}{\rho}\frac{g}{p^*}\frac{\partial p'}{\partial \sigma} + \frac{g}{\gamma}\frac{p'}{p} &= -\mathbf{V}\cdot\nabla w + g\frac{p_0}{p}\frac{T'}{T_0} \\ -\frac{gR_d}{c_p}\frac{p'}{p} + e(u\cos\alpha - v\sin\alpha) &+ \frac{u^2+v^2}{r} + D_w,\end{aligned} \tag{4}$$

Thermodynamics

$$\begin{aligned}\frac{\partial T}{\partial t} = -\mathbf{V}\cdot\nabla T + \frac{1}{\rho c_p}&\left(\frac{\partial p'}{\partial t} + \mathbf{V}\cdot\nabla p' - \rho_0 g w\right) \\ &+ \frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0}D_\theta,\end{aligned} \tag{5}$$

where p, ρ, T are pressure (Pa), density ($\mathrm{kg}\cdot\mathrm{m}^{-3}$), and temperature (K), respectively. The subscript "0" represents the reference-state. u, v, w are component of wind velocity ($\mathrm{m}\cdot\mathrm{s}^{-1}$) in eastward, northward, and vertical direction, respectively. Q is diabatic heating rate per unit mass ($\mathrm{J}\cdot\mathrm{kg}^{-1}\cdot\mathrm{s}^{-1}$). c_p is specific heat at constant pressure for dry air. $\gamma = c_p/(c_p - R)$ is ratio of heat capacities. $R = 287\mathrm{J}\cdot\mathrm{kg}^{-1}\cdot\mathrm{K}^{-1}$ is ideal gas constant. θ is potential temperature (K). D_A is diffusion and PBL tendency for variable A. m is map-scale factor. $p' = p - p_0$ is perturbation pressure (Pa). $p^* = p_s - p_t$, p_s and p_t are surface and top pressures respectively of the reference state. $\sigma = (p_0 - p_t)/(p_s - p_t)$ is nondimensional vertical coordinate of model. f is Coriolis parameter, $e = 2\Omega\cos\lambda$, $\alpha = \phi - \phi_c$, Ω is angular velocity of the earth, λ is latitude, ϕ is longitude, and ϕ_c is central longitude. r is the radius of the earth.

$$\mathbf{V}\cdot\nabla A \equiv mu\frac{\partial A}{\partial x} + mv\frac{\partial A}{\partial y} + \dot{\sigma}\frac{\partial A}{\partial \sigma}, \tag{6}$$

$$\dot{\sigma} = -\frac{\rho_0 g}{p^*}w - \frac{m\sigma}{p^*}\frac{\partial p^*}{\partial x}u - \frac{m\sigma}{p^*}\frac{\partial p^*}{\partial y}v, \tag{7}$$

$$\begin{aligned}\nabla\cdot\mathbf{V} = m^2\frac{\partial}{\partial x}\left(\frac{u}{m}\right) - \frac{m\sigma}{p^*}\frac{\partial p^*}{\partial x}\frac{\partial u}{\partial \sigma} + m^2\frac{\partial}{\partial y}\left(\frac{v}{m}\right) \\ -\frac{m\sigma}{p^*}\frac{\partial p^*}{\partial y}\frac{\partial v}{\partial \sigma} - \frac{\rho_0 g}{p^*}\frac{\partial w}{\partial \sigma}.\end{aligned} \tag{8}$$

The derivations of above model equations (1)-(5) are based on the gas law and first law of thermodynamics. More details can be found in (Grell et al., 1995; Dudhia et al., 2005). Obviously, MM5 is a 5-dimensional model of partial differential equations with structure of coupled variables, which causes its solving time consuming. Currently, the forecast of MM5 can only achieve hourly updation. To implement real-time forecast of wind, simplifications have to be made.

3 SIMPLIFICATION TO MM5 FOR WIND FORECAST

Comparing with weather forecast, wind forecast for wind turbines has its own uniqueness.

1. The rotor blade length of wind turbine is usually less than 150m, so the pressure change along the vertical direction for wind turbine is not too much.
2. The rotation of wind turbine is not driven by the vertical pressure on the blade, but by the horizontal velocity difference on its top and bottom surfaces. Pressure or vertical velocity has less contribution.
3. Temperature may not be a necessary option in real-time forecast as the rotation of wind turbine is not sensitive to temperature change.

Thus, the MM5 model of equations (1)-(5) can be simplified in the following way:

For real-time forecast, the time interval of two continuous predictions should be very small, say one minute. In such a short period, temperature changes can be neglected. Therefore, $\partial T/\partial t = 0$, $\mathbf{V}\cdot\nabla T = 0$ and (5) becomes

$$\frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0}D_\theta = -\frac{1}{\rho c_p}\left(\frac{\partial p'}{\partial t} + \mathbf{V}\cdot\nabla p' - \rho_0 g w\right). \tag{9}$$

Substituting (9) into (1) yields

$$\frac{\partial p'}{\partial t} - \rho_0 g w + p\nabla \cdot \mathbf{V} = \mathbf{V} \cdot \nabla p', \tag{10}$$

since $p/(\rho T c_p) = 1 - \gamma^{-1}$ according to gas law. Thus, (1) is simplified to be (10) and model dimension is reduced as (5) is missing.

As pressure changes along the vertical direction of wind turbine is not too much, $\partial p'/\partial z \approx 0$. By the coordinate transformation $(x,y,z) \rightarrow (x,y,\sigma)$,

$$\left(\frac{\partial}{\partial x}\right)_z \rightarrow \left(\frac{\partial}{\partial x}\right)_\sigma - \left(\frac{\partial z}{\partial x}\right)_\sigma \frac{\partial}{\partial z}, \tag{11}$$

where $\mathrm{d}z = -\mathrm{d}p_0/(\rho_0 g) = -(p^*\mathrm{d}\sigma + \sigma \mathrm{d}p^*)/(\rho_0 g)$, so

$$\left(\frac{\partial}{\partial x}\right)_z \rightarrow \left(\frac{\partial}{\partial x}\right)_\sigma - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial x}\frac{\partial}{\partial \sigma}. \tag{12}$$

Thus,

$$\left(\frac{\partial p'}{\partial x}\right)_z \rightarrow \left(\frac{\partial p'}{\partial x}\right)_\sigma - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial x}\frac{\partial p'}{\partial \sigma} = 0, \tag{13}$$

$$\left(\frac{\partial p'}{\partial y}\right)_z \rightarrow \left(\frac{\partial p'}{\partial y}\right)_\sigma - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial y}\frac{\partial p'}{\partial \sigma} = 0, \tag{14}$$

and (2) and (3) can be simplified as

$$\begin{aligned}\frac{\partial u}{\partial t} &= -\mathbf{V} \cdot \nabla u + v\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right)\\ &\qquad - ew\cos\alpha - \frac{uw}{r} + D_u, \end{aligned}\tag{15}$$

$$\begin{aligned}\frac{\partial v}{\partial t} &= -\mathbf{V} \cdot \nabla v - u\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right)\\ &\qquad + ew\sin\alpha - \frac{vw}{r} + D_v. \end{aligned}\tag{16}$$

If ignoring the effect of vertical velocity w on horizontal momentum, (15) and (16) can be further simplified as

$$\frac{\partial u}{\partial t} = -\mathbf{V} \cdot \nabla u + v\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right) + D_u, \tag{17}$$

$$\frac{\partial v}{\partial t} = -\mathbf{V} \cdot \nabla v - u\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right) + D_v. \tag{18}$$

By the above approximation, MM5 model is simplified as (10), (17) and 18) with less dimensions and variables, which is suitable for the real-time prediction.

4 BOUNDARY CONDITIONS

Both MM5 and simplified model are composed of partial differential equations where only numerical solutions are available. Thus, boundary conditions have to be set in addition to initial values prior to running a simulation. Here in our real-time wind forecast, wind velocity, temperature and pressure are specified as boundaries.

The boundary values can come from real-time observations of the wind. In this case, some weather stations have to be set up at the outer place of the wind power plant for measurement. The distance from one station to one wind turbine is a trade-off between prediction accuracy and computation burden. The nearer the station is to the wind turbine, the more accurate the wind prediction, but the less time for solving the equations. Alternatively, the boundary values can come from another model's forecast (in real-time forecasts).

The shape of the boundary can be determined freely, depending on the convenience of computation. Rectangle and circle are two types broadly used. The area surrounded by the boundary is then grided evenly and every grid point gives a wind prediction after solving the model numerically. Normally, the wind turbine should be one grid point inside the boundary. But due to its unevenly distribution, this is usually not the case. Therefore, linear interpolation has to be applied to give the final wind prediction.

5 ERROR CORRECTION

To improve the forecast accuracy, some "feedback" strategy should be introduced for error correction by comparing the estimated and true values. This can be done by Kalman filter. Thus, the loss of accuracy caused by the model simplification can be made up, but computation increases inevitably. Therefore, trade-off should be made between model simplification and Kalman filter design.

6 SIMULATIONS

To verify whether the proposed model can give real-time forecast of wind, a simulation has to be conducted. Two ways are available to this end. One is to use the code of MM5 model, which is available at the web site of National Center for Atmospheric Research (NCAR) for free download. The other one is to apply the Matlab Toolbox of partial differential equation to the proposed model. This part of work is still under study and will supplemented in the final version if possible.

7 CONCLUSIONS

This paper proposed a real-time wind forecast model for wind energy industry by simplifying the existing MM5 model of weather forecast. Details of the simplification method is given as well as other issues on model implementation. To our best knowledge, no similar model is available for wind forecast in wind energy industry so far.

REFERENCES

Anthes, R. A. and Warner, T. T. (1978). Development of hydrodynamic models suitable for air polpollution and other mesometeorological studies. *Mon. Wea. Rev.*, 106:1045–1078.

Dudhia, J., Gill, D., Manning, K., Wang, W., and Bruyere, C. (2005). *PSU/NCAR Mesoscale Modeling System Tutorial Class Notes and Users' Guide (MM5 Modeling System Version 3)*. National Center for Atmospheric Research, USA.

Grell, G. A., Dudhia, J., and Stauffer, D. R. (1995). *A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)*. National Center For Atmospheric Research, USA.

Joensen, A., Giebel, G., Landberg, L., Madsen, H., and Nielsen, H. A. (1999). Model output statistics applied to wind power prediction. In *Proceedings of European Wind Energy Conference*, pages 1177–1180, Nice, France.

Kazuhito, F., Jun, Y., Akira, T., Tomonao, K., and Takashi, Y. (2006). Wind power generation forecast using the real-time local weather forecasting system. *Wind Energy*, 30(1):92–98.

Landberg, L. (1999). Short-term prediction of the power production from wind farms. *J. Wind Eng. Ind. Aerodyn.*, 8:207–220.