Distributed Model Predictive Control of Wind Farms[1]

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Abstract
Wind turbines in a wind farm operate individually to maximize their own power. Wind farm control can be used to coordinate turbines to improve the performance of the full wind farm. A distributed model predictive control method for accomplishing power tracking in wind farms is presented. Individual wind turbines are treated as subsystems that share limited information with their nearest neighbors. Through iteration of the communication, the distributed method converges to the centralized solution. This method is advantageous for large wind farms as it is computationally efficient and can operate in real-time.
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Introduction
Wind energy is a rapidly growing industry, as evidenced by the over 5-fold increase of installed global capacity over the last decade [1]. Due to economies of scale regarding manufacturing and grid integration, as well as decreasing availability of wind sites, wind turbines are generally grouped together in wind farms. However, when located near one another, individual wind turbines can have significant effects on the performance of the other turbines around it stemming from aerodynamic interactions [2]. These effects are caused by the fact that as a wind turbine extracts power the overall speed of the wind in the wake behind the turbine is decreased, thus decreasing the wind power available to downstream turbines within this wake. Additionally, turbines can introduce turbulence in wakes that result in unwanted structural loads on downwind rotors. For these reasons, there has been growing interest in research regarding control of wind farms with the goal of increasing total farm power production and mitigating turbine loads. This paper presents a coordinated control strategy for wind farms that determines control actions at the local turbine level to optimize wind farm performance at a global level, leveraging a distributed control algorithm developed for coupled and constrained systems.

Method
The algorithm used in this paper, known as Limited-Communication Distributed Model Predictive Control (LC-DMPC) [3], divides the global control problem into individual subsystems that are subject to the upstream effects of neighboring systems as well as producing outputs that influence downstream systems. An overview of this structure is given in Figure 1. LC-DMPC only requires communication between the nearest neighbors and each subsystem solves its own objective function as opposed to the traditional centralized function, enabling implementation across large scales. Through iteration of the communication, the local optimizations converge to the global centralized solution. With wind farms, the subsystems become the individual turbine wakes. The turbines are given power tracking references that are driven by power regulation for the grid. The optimization determines

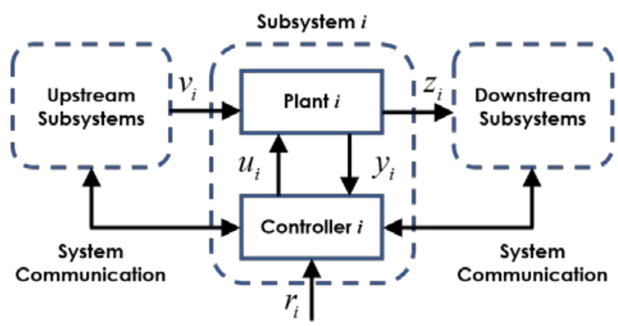

Figure 1- LC-DMPC system structure, figure adapted from [3].

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setpoints for yaw misalignment and axial induction factor for the turbines to follow that balances tracking the reference power signals and the amount of control action used. The turbine wakes are linearly modelled as:

$$\delta^{k+1} = \delta^k + c_1 c_2 \bar{a}\left(\theta_u^{k-N} - \theta_u^{k-N-1}\right) \quad \sigma^{k+1} = \sigma^k + c_3\left(a_u^{k-N} - a_u^{k-N-1}\right) \quad u^{k+1} = u^k + c_6\left(a_u^{k-N} - a_u^{k-N-1}\right) \tag{1}$$

where δ, σ and u are the wake deflection, wake width, and wake centerline velocity respectively. The superscript ^{k} denotes the discrete timestep while the subscript $_u$ denotes parameters from upwind turbines. N is the number of discrete timesteps for the upwind turbine's control actions to propagate to the downwind turbines. θ is the yaw angle of the turbine and a is the axial induction factor. The constants c_1, c_2, c_3 and c_6 are derived from wake characteristics defined in [4,5,6] and are omitted here for brevity. The yaw and thrust control are described as simple proportional controllers. The output of the subsystems is the power generated by the turbines defined as:

$$P(t) = \frac{1}{2}\rho A C_{P,d} \cos^2(\theta_d) U_d^3 \qquad C_p(a_i) = 4a_i(1-a_i)^2\eta \tag{2}$$

where ρ is the air density, A is the rotor area, C_p is the power coefficient, and η is the loss factor as defined in [7]. A linearized state-space representation of the subsystems is formed as:

$$\dot{x}_i = A_i x_i + B_{u,i} u_i + B_{v,i} v_i \qquad y_i = C_{y,i} x_i \qquad z_i = C_{z,i} x_i + D_{z,i} u_i \tag{3}$$

where x are the states, u are the control inputs (yaw misalignment and axial induction factors of individual turbines), and v is the vector of upstream inputs. These are defined as:

$$x_i^k = \left[\delta_i^k,\ \sigma_i^k,\ u_i^k,\ \theta_i^k,\ \theta_i^{k-1},\ a_i^k,\ a_i^{k-1}\right]^T \quad u_i^k = \left[\theta_{i,r}^k,\ a_{i,r}^k\right]^T \quad v_i^k = \left[\theta_{i,u}^{k-N},\ \theta_{i,u}^{k-N-1},\ a_{i,u}^{k-N},\ a_{i,u}^{k-N-1}\right]^T \tag{4}$$

The objective function that is minimized is given by:

$$\min_{u_i} J_i = \sum_{b=1}^{N_p} e_{i,b}^T Q_{i,b} e_{i,b} + u_{i,b}^T S_{i,b} u_{i,b} + \Psi_{i,b}^T z_{i,b} \tag{5}$$

where N_p is the prediction horizon length, e is the vector of errors between the power reference signal and the output power, u is the vector of control inputs, Ψ is the vector of penalty terms representing the sensitivity of the objective function to the subsystem's upstream inputs. For this implementation, the reference signals, r, are power signals to provide active power control of the wind farm. The selected references are given to ensure reliable performance for grid services and integration.

Results and Expected Conclusions

We will present simulation results of applying the LC-DMPC method at WindTech2017. The LC-DMPC method will be compared against the centralized MPC solution. The expected results are that the individual turbines will find an optimal balance between power production and wake deflection/axial induction to provide power tracking sufficient for typical grid demands.

Future efforts will focus on optimizing for maximum power production, introducing a disturbance term in Equation (3) to include uncertainty in wind speed and wind direction, and investigating nonlinear MPC to compare to the linearized models used here.

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