Integration of a Meandering-Capturing Wake Model into Model Predictive Control for Dynamic Wind-Farm Operation

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Abstract:
Wind-farm-scale control increasingly requires flow-aware strategies able to react to the turbulent, unsteady and heterogeneous nature of atmospheric inflow. Classical control strategies - based on steady-state wake models - perform well for power maximization in steady conditions [1] but degrade in dynamically evolving situations [2, 3] and cannot reliably support short-horizon tasks such as power tracking. This motivates integrating unsteady wake physics, including wake meandering, into real-time control architectures.

This work incorporates the medium-fidelity, meandering-capturing wake model *OnWaRDS* [4] into a Model Predictive Control (MPC) framework. *OnWaRDS* is a computationally efficient Lagrangian wake model that predicts wake advection, meandering, and turbine–turbine interactions several minutes ahead while assimilating rotor-based flow measurements to estimate inflow conditions [5]. In addition to these model-based predictions, the controller and its underlying flow predictions are assessed in a realistic turbulent flow field generated by high-fidelity Large-Eddy Simulations (LES) coupled to an Actuator Disk representation [6].

Because adjoint-based MPC would require significant restructuring of the model, the control is implemented using the derivative-free Covariance Matrix Adaptation Evolution Strategy (CMA–ES). This approach leverages *OnWaRDS*' predictive capabilities while allowing efficient optimization in nonlinear, unsteady wind-farm environments.

The controller is evaluated in a two-turbine NREL-5MW layout under turbulent inflow. Two control scenarios are considered: (i) yaw-based wake steering for power maximization, and (ii) power-setpoint tracking through collective pitch control. As shown in Fig. 1, the yaw-based MPC achieves a mean farm-level power increase of approximately 10% relative to standard operation. The predicted wake fields generated by the controller (Fig. 2) reveal that this gain is achieved by optimally redirecting the upstream wake, increasing the downstream turbine's power recovery. In the regulation scenario, the farm follows a prescribed power trajectory within a tight tolerance band (Fig. 1), while reduced induction leads to weaker wake deficits (Fig. 2). The yaw-command evolution (Fig. 3) shows that once the optimal setpoint is reached, control activity remains minimal, indicating stable and actuator-efficient operation.

These results highlight the potential of turbulence-resolving wake models embedded within MPC for achieving dynamically responsive wind-farm control. Ongoing work focuses on the imposition of actuation-rate constraints, evaluation under transient inflow and operational scenarios, and the integration of real-time load proxies to enable multi-objective control balancing power extraction and fatigue mitigation.

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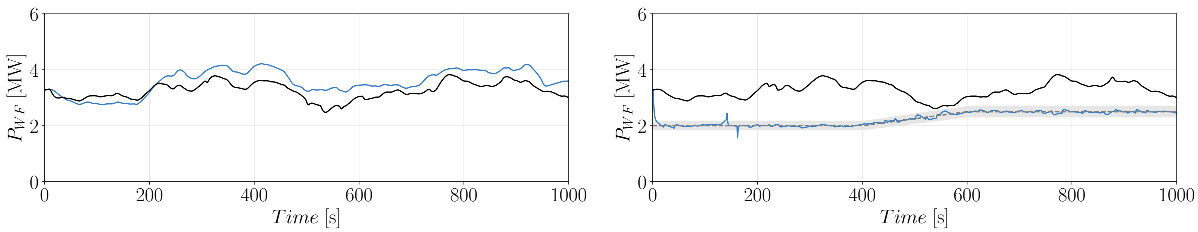

Figure 1: **Wind farm power for yaw control (YAW, left) and power-regulation control (REGUL, right).** These time series correspond to 1000 s simulations of two inline NREL-5MW turbines separated by 7D and subjected to 8 m/s inflow with 6% turbulence intensity. Controlled cases (blue lines) are compared against a baseline greedy controller for the turbines (STD, black lines). In the **YAW** case, the controller increases the total farm power relative to the STD baseline. In the **REGUL** case, the farm accurately tracks the prescribed power command (grey dashed line) within ±7.5%.

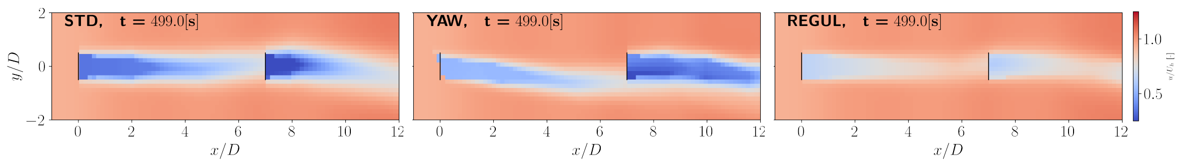

Figure 2: **Instantaneous streamwise velocity fields (STD, YAW, REGUL), predicted using *OnWaRDS*.** In **STD** operation, the downstream turbine experiences a strong, centered wake deficit. Under **YAW** control, the upstream wake is deflected laterally, significantly increasing downstream recovery. Under **REGUL** control, reduced induction leads to a weaker wake deficit. These differences illustrate how MPC leverages predicted meandering dynamics.

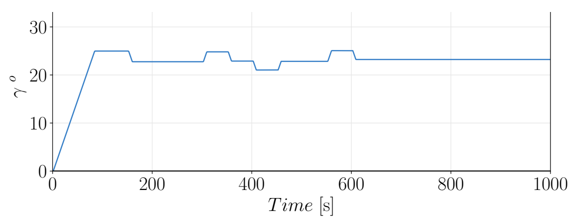

Figure 3: **Yaw-angle command for the upstream turbine (YAW case).** The controller converges to an optimal yaw misalignment of approximately 22°, and actuator activity becomes minimal once this optimum is reached. The stable yaw behavior shows that unsteady wake-aware MPC achieves similar optima as steady-state methods while dynamically adapting to turbulence.

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