Predictor-Based Extremum Seeking for Optimal Wake Steering in Wind Farms

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A wind turbine extracting momentum from the incoming flow generates a wake, a downstream region of reduced velocity that recovers only over several rotor diameters, so that in commercial farms, where turbine spacings are of that same order, these wakes substantially reduce the power extracted by downstream turbines [1]. *Wake steering*, the deliberate yaw misalignment of upstream rotors in order to deflect their wakes away from the downstream rotors, is the most advanced of the available actuation mechanisms in terms of commercial realization [2]. Current practice is model-based and quasi-static: a steady-state wake model is calibrated offline and the yaw set-points maximizing the predicted farm power are computed from it [3], then deployed in the field as a look-up table indexed by the ambient conditions [4]. Field campaigns demonstrate the potential of this approach but also reveal its limitations: the realized gains depend strongly on the ambient conditions, being higher and more consistently realized in stable atmospheric conditions than in unstable ones [4], and the performance of this open-loop architecture depends strongly on the accuracy of the underlying model [2]. This motivates *model-free* extremum seeking (ES), which updates the set-points directly from power measurements [5].

The principal difficulty at farm level is that a wind farm does not constitute a static map. Control-oriented dynamic wake models represent the wake as a transport equation advected by the free-stream flow [6], so that a yaw variation at an upstream turbine affects a downstream rotor only after the perturbed wake has traversed the inter-turbine distance. For spacings of several hundred metres, the resulting transport delays range from tens of seconds to minutes and differ between channels. They are furthermore inherently time-varying whenever the wind speed is. Such delays destabilize classical ES [7]. Since the dither is not advanced to compensate them, each channel delay reappears in the recovered gradient as a multiplicative cosine factor that may vanish or change sign. Within the standard averaging analysis the delay can then only be accommodated by lowering the dither frequencies, which drastically slows convergence [8].

In this contribution and starting from the transport model, farm power maximization is reformulated as a static optimization coupled through multiple, distinct, time-varying input delays, the delay structure being identified from the flow physics rather than postulated. A predictor-based multivariable ES scheme, formulated in both gradient- and Newton-based form and following the multiple-delay ES designs of [7], compensates these delays channelwise using only real-time farm-power and free-stream wind-speed measurements and no wake-model parameters. Three aspects are specific to the application. First, the steady farm power factorizes exactly as a cube in the wind speed, so that the optimal yaw configuration is wind-speed invariant. Second, the scheme uses a smooth ternary dither carrier whose zero-hold interval and bounded slew rate enable the yaw actuator to follow the excitation without violating its rate limit, and an averaging argument establishes that gradient and Hessian recovery is preserved. Third, the formulation localizes exactly to any turbine cluster, so that large farms decompose into independent, parallelizable ES instances.

The scheme is evaluated on a three-turbine array against a non-causal optimal control benchmark that maximizes farm power with the entire wind trajectory known. The channel delays follow from the wake advection and reach 95 s at 9 m/s. With a single fixed tuning, both predictor laws converge from greedy (zero-yaw) initialization and yield a farm-power increase of 3 to 4% over greedy operation between 7 and 12 m/s, attaining 98.7 to 100.2% of the benchmark, whereas the uncompensated scheme is destabilized at the same dither frequencies. A measured hub-height wind record confirms that the same tuning tracks the optimizer under genuinely time-varying delays.

References

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