Hierarchical wind farm control for power/load optimization

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This paper describes the control concept for wind farm power/load optimization with emphasis on compensation of disturbances present in a wind farm. The control concept was developed for the EU-FP7 project Aeolus. The Aeolus project approaches the wind farm control problem by considering wind turbines in a wind farm as individual power actuators affected by constraints. It is assumed that the demanded wind farm power production is given in advance, i.e., the power reference value for the whole farm is provided by the Transmission System Operator (TSO). The supervisory farm controller then distributes the power demand among wind turbines based on the dynamic model of wind field inside wind farm. The objective of distribution is to minimize the cumulative load of all wind turbines in wind farm, while respecting the system constraints and fulfilling the TSO demands.

1 Supervisory wind farm control problem

The idea behind power/load optimization in Aeolus project is the employment of the wind field model that describes the dynamic development of wakes inside a wind farm [1, 2]. From a control perspective, the wakes impose coupling between individual wind turbines. Namely, a wind turbine standing in a wake created by an upwind turbine experiences reduced wind speed and increased turbulence, which influence its loading and power production potential. The motivation for proposed wind farm optimization lies in the fact that wake effects generated by a wind turbine can be influenced by changing its power reference (a wind farm control variable). Combination of the wind field model and models of wind turbines yields an overall dynamic wind farm model suitable for optimization. Since this system involves many constraints, which are related mostly to wind turbine operation and the goal is optimizing the production, a natural choice for control design framework is the Model Predictive Control (MPC).

A centralized approach to the optimization of large wind farm operation is an extremely complex control problem. Namely, the governing system is best described as a coupled, constrained multiple-input multiple-output model whose order grows very fast with the size of wind farm. Furthermore, the wind turbine and especially the wind field are highly nonlinear systems. Also, the system is subjected to large number of disturbances due to random nature of wind, as well as due to random wind turbine malfunctions that may prevent or restrict its operation. Finally, wind farm model inherently comprises processes acting on very different time scales: the behavior of a typical megawatt scale wind turbine with local speed and power controller has dominant dynamics in the time scale of 1 second, while the typical propagation time of wind between two rows of wind turbines can be significantly longer than 10 seconds.

One of the primary demands on the wind farm controller set in the Aeolus project is the scalability of the control algorithms to wind farms of different sizes. We note that the wake effects described above appear only in large wind farms, and for such farms computation of a centralized

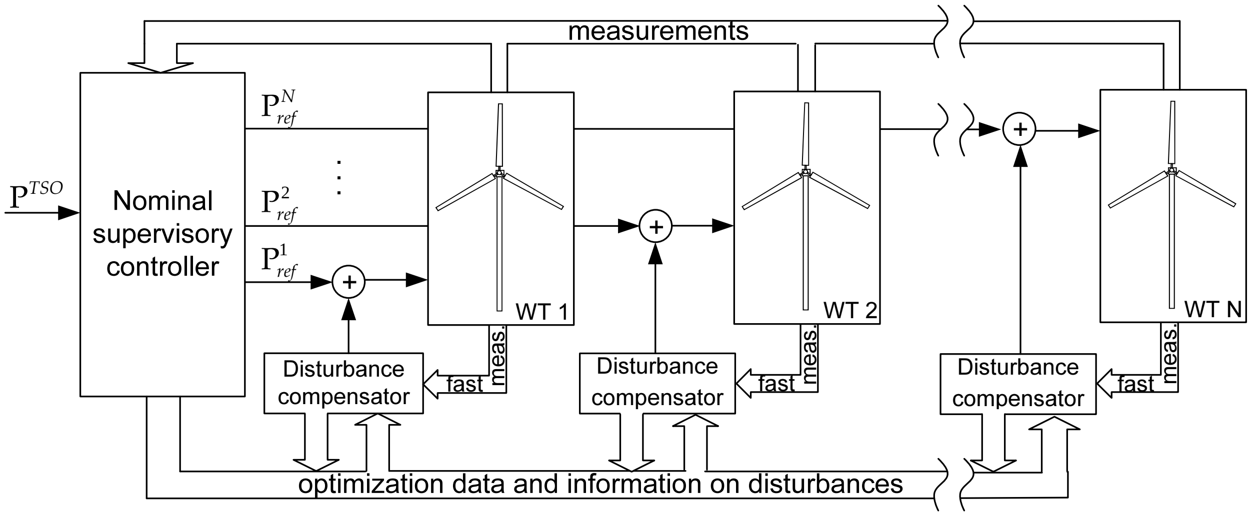

Figure 1: Wind farm hierarchical control system

model predictive controller might be computationally intractable for practical, real-time applications. As an illustrative example consider the wind farm that comprises 16 rows of wind turbines separated by 200 meters. For wind speed of 15 m/s the prediction horizon should ideally be around 200 seconds in order to capture the wind propagation through entire farm. With 1 second sampling time that would mean the computation of optimization problem with hundreds of optimization variables with prediction horizon of 200 samples in less than 1 second. To circumvent the need to solve such complex optimization problems in this paper we propose the hierarchical supervisory control concept adapted to the application at hand.

2 Hierarchical wind farm control concept

The wind farm dynamics are effectively decoupled through different time scales. A two level hierarchical control concept is proposed that is utilizing this fact as a separation principle. The top level of control – the nominal supervisory controller – considers the propagation of mean wind stream through the wind farm and therefore accounts for the coupling that emerges due to wakes. This level of control derives the overall optimal wind farm operating point. The sampling time of this level can be adjusted to the size of wind farm and to separations of wind turbines inside a wind farm. The bottom level of control works at faster sampling rate and accommodates the nominal controller's operating point to disturbances that occur on faster time scale, e.g. the influence of local wind gusts (i.e. the wind gusts that are not predicted by wind flow model) or sudden shutdown of a wind turbine. An implicit assumption is that the overall wind field in a wind farm and the short time scale disturbances are to a large extent decoupled. The intuitive reasoning is that because the local disturbances affect the wind field only locally then the operating point computed by the nominal controller is still valid for the largest part of the wind farm. Therefore, the objective of the disturbance compensation is to remain as close as possible to optimal operating point set by the nominal controller, while at the same time handling disturbances and respecting any newly imposed constraints.

The proposed control scheme is a two level hierarchical control concept with communication going only one way – top to bottom. The top level receives information (measurements) at slower sampling rates and the bottom level on faster sampling rates. The bottom level has a reduced computational effort since it does not need to handle the wind field model. The Fig. 1 shows the schematics of the proposed control concept. Similar control concept for multi time scale systems was described in [3].

3 Scope of the work

This paper describes the hierarchical control concept for supervisory wind farm control. The focus is on integration of disturbance compensator in the overall wind farm control. Such a control structure has been proposed in order to mitigate the computational load of the supervisory controller. Thanks to the time-scale decoupling one can achieve effective relaxation/decoupling of the optimal control problem. The design of the disturbance compensator resides on the following objectives:

- provide rejection of disturbances on fast time scale,
- respect system constraints,
- keep loads experienced by the wind turbine small, and
- remain as close as possible to distribution of power references provided by the nominal controller.

The idea of the solution we introduce can be loosely summarized as follows.

1. *For each wind turbine formulate a local finite time optimal control problem. Objective function has to penalize load experienced by wind turbine and deviation from power reference provided by the nominal control.*
2. *Obtain sensitivity functions of local costs and turbine loads to the changes in wind turbine power trajectory, where the real wind turbine state (measurements) are used as parameters.*
3. *Obtain parametric expression for the optimal controller. One group of parameters are the state measurements and the other define the power trajectory.*
4. *Impose global objective :* $\sum_{i=1}^{N} P^i = P_{TSO}$*, where* P^i *is the power produced by the i-th wind turbine,* P_{TSO} *is the wind farm power demand provided by TSO and* N *is number of wind turbines in the wind farm.*
5. *Find such control actions that satisfy global objective and produce as small as possible increase in the local cost functions [4].*

Note that computationally demanding steps 1–3 are performed off-line [5].

References

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