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Control Co-Design Using a Nonlinear Wind Turbine Dynamic Model Based on OpenFAST Linearization

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Abstract—Offshore wind is an abundant renewable energy source that has the potential to be tapped more thoroughly through wind turbines designed specifically for offshore installation. At the emerging current state of large-scale offshore wind system development, reducing the Levelized Cost of Energy (LCOE) is a critical factor in establishing economic feasibility. A significant portion of cost is due to the complexities of offshore wind turbines and the relatively expensive installation and operation costs at the offshore sites. Control Co-Design (CCD) with Open-Loop Optimal Control (OLOC) methods can provide meaningful insights for achieving lower LCOE with unprecedented efficiency via simultaneously solving optimal design problems in both physical system (plant) and control system domains, assuming the full availability of information, such as future wind state and ultimate flexibility of control. However, currently available dynamic models have limitations when used in conjunction with the established CCD strategies based on OLOC solved by direct collocation methods. Optimizers need to directly access the dynamic model's time derivative function and modify dynamics externally; current state-of-the-art wind turbine dynamic models, such as OpenFAST, often do not provide direct access to the time derivative function. Here, we present an alternate OLOC CCD optimization strategy based on a large number of linearized OpenFAST models that are generated over varied wind speed and plant design variable values to construct a surrogate model trained to simulate the derivative function of the dynamic behavior of the nonlinear OpenFAST model. With this derivative function surrogate modeling (DFSM) strategy, the direct collocation method has online access to an approximate time derivative function, and the time-domain dynamics can be solved using the quadrature method associated with the collocation solver. For the demonstration study presented here, during the DFSM training stage four hundred OpenFAST inputs are created with the Enhanced Stochastic Evolutionary (ESE) sampling method to capture the dependence of dynamics on five plant design variables. Complete simulation cases are solved for a wide range of steady wind speed points, resulting in linearized OpenFAST models at each training point to produce a surrogate model input space with six dimensions. A Kriging model with Partial-Least Squares (KPLS) is used to construct the DFSM. In the design optimization stage, a CCD problem is solved using the nested formulation. Covariance Matrix Adaptation Evolution Strategy (CMA-ES) is used for exploring the plant design variable space in the outer loop of the optimization formulation, and the Legendre-Gauss-Lobatto pseudospectral collocation method is used to solve the inner-loop optimal control problem using the DFSM constructed in the earlier stage. While the DFSM strategy based on massive linearization data is found to be useful in replacing detailed state-of-the-art dynamic models, there exist a few drawbacks and limitations. The method involves a relatively high computational expense when sampling and training the DFSM. Also, there exists a possibility that the optimal solution may converge to inaccurate, incorrect, or unexpected dynamic responses when using this approximation strategy, especially when the inner-loop optimizer explores control schemes outside of the envelope of the traditional controller used when generating training data for the DFSM.

Keywords—offshore wind energy, derivative function surrogate modeling, control co-design, open-loop optimal control, linearization