Optimum design of slender and tall wind turbine tower for residual vibration reduction

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Abstract

As the competition in wind power market becomes fiercer and the demand for profit grows stronger, the need for tall wind turbine towers has grown dramatically. The wind load of tall towers is stronger and more stable, which improves power generating efficiency, yet presents new challenges to strength, stability and fatigue design of these towers. Since the high cost of rigid tower design, slender tower is preferred. However, the excessive vibration due to resonance during startup operation is also an issue of great concern for tall and slender tower.

Apart from normal scheduled shutdowns, a number of hazardous situations require shutting down the WTG(Wind Turbine Generator) as fast as possible to prevent damages and bring it to a safe state. This includes shutdown due to high wind speeds as well as rapid shutdown triggered by the loss of generator torque or pitch control, faulty sensors and actuators, or hazardous conditions such as blade icing. This is referred as emergency shutdowns (EST) in literature, which is a complementary protective measure. Strong long-time residual vibration of the tower top and dramatically vibrated structural loads at typical sections of the tower are observed after EST, which poses imminent threat to their safe operation, especially to tall and slender towers. Intensive studies of the shutdown procedure and optimal control of blade pitch angles has been seen in literature. For simplicity, the present paper considers the structural vibration after the shutdown as a residual vibration under an impact due to the shutdown operation.

To reduce the construction cost and ensure the safe operation of wind turbine towers, a frequency control based structural optimization, subject to residual vibration constraints, is presented in this work. For the sake of simplicity, a single tubular wind turbine tower is considered and modeled as a cantilever structure, and the platforms and ancillary structures neglected. The design variables are cross section parameters and subject to their upper and lower bound constraints based on manufacturing and logistic consideration. For example, for steel tubular tower the external diameter and the thickness of each section of the tower are design variables. The objective function is minimum structural volume and the natural frequency is constrained to ensure the tower a slender design. A quadratic integral index which measures the residual vibration after EST globally is constrained to control the effect of EST. With the Lyapunov's second method, the quadratic integral index is simplified into matrix forms, which avoid the transit dynamic analysis for residual vibration and reduces computational time to a great extent.

The optimization process mainly includes internal and external cycle. In the internal cycle, the increments of the design variables are updated by method of moving asymptotes (MMA). In the external cycle, the constraints and their sensitivities to the design variables are calculated. The sensitivities of the residual vibration constraints with respect to design variables are obtained by adjoint method and solution of Lyapunov equation.

For comparison with the constraint on integral residual vibration, the constraint on tower top displacement under the wind load at shut-down is examined to study its effect on optimum design. The professional software Bladed is applied to obtain the wind load at EST, which makes the study more relevant in industrial applications. The tower top displacement and its sensitivities to design variables can be calculated by Mohr integration.

The results of the two examples indicate that the residual vibration constraint and the displacement constraint have similar effect in controlling residual vibration after EST. But the optimal structure has different optimal topologies in accordance to different Rayleigh damping coefficients.

Keywords: Wind turbine tower; Slender tower; Optimization design; Residual vibration; Emergence shutdown;