Structured summary of the dissertation with the title:

„Investigation of a medium-sized floating offshore wind turbine with stall regulation"

Submitted by M.Sc Moe Moe Aye

The starting point of this thesis is a conceptual design of a medium-size floating wind turbine that can be used for decentralized energy supply. It was developed within the frame of research project CART (Compact and Robust Medium-sized Wind Turbine) in cooperation with the Chair of Wind Energy Technology the University of Rostock, several German companies, the Vietnam National University, and several companies in Vietnam. The goal of the present study is to develop a control and protection concept on the basis of a fully integrated load analysis. This means in the simulation all relevant aspects contributing to the loading of the turbine like wind, waves, vibrations and the controller are taken in consideration.

For floating offshore wind turbines like CART, the major challenges are related to the dynamics behaviors of the system in response to combined wind and wave loading and the choice of power regulation. The wind turbine needs to have an efficient power regulation that can optimize power output, provide the highest possible efficiency in normal operation and ensure safe operation during grid loss or storm conditions. Of equal importance, power regulation must ensure that the structural loads are reduced especially when exposed to constantly changing environments like wind gusts and turbulence. Moreover, the coupling of aerodynamic forces, structural forces, and hydrodynamic forces can lead to large amplitude motions. Therefore, load analyses are necessary to characterize the global dynamic behavior of the coupled model, identify design driving loads, and highlight the impact brought about the floating substructure.

For this purpose, a control concept was developed to ensure the highest possible efficiency in normal operation. Then, the protection concept was developed to ensure safe operation during grid failure or storm conditions. The feasibility of the proposed control concept was evaluated for both land- and sea-based CART hypothetical wind turbine and the results are elaborated on the ultimate loads and fatigue loads of several load components.

The following results can be drawn from the present study:

- A simple stall regulation concept was proposed for the investigated hypothetical wind turbine to maximize the power output in the partial load region and to limit the power output in the full load region. The feasibility of the developed control concept was evaluated by simulating the turbine under steady wind conditions. Based on the resulted mean value, standard deviation, and maximum values of the response of the control system, the implemented torque control concept seems to be stable for the given control parameters. CART machine utilizes no active control system like blade tip brake to reduce the rotor speed in very high winds. Instead, it uses a mechanical brake to bring the turbine to a standstill in very high winds. It was assumed that it takes 0.3 s to activate the shaft brake, and 0.5 s of time lag for the brake to reach its maximum brake torque. Moreover, it was assumed that a brake torque of 55 kN-m is achieved in its fully deployed state for an emergency or a fault condition, parking in storm condition, and overspeed protection. The torque controller does not contain start-up and shutdown logic in the present study. Therefore, the feasibility of shaft brake was evaluated rather by simulating grid loss followed by the shaft brake. It was observed that the transient response in all parameters dissipated within quite reasonable time. The overshooting due to this transient event seem reasonable for the given wind speed. Overall, the outcomes of the initial stage of the work indicate that the developed control concept can contribute to power stability quite well. Thus, it serves as a good starting point to further investigate the global dynamic behaviors of the integrated system in different operational conditions.
- Because stall-regulated wind turbines have no active aerodynamic control system to reduce the rotor thrust force in high winds, it was observed that the load responses to be more specific mean values of most parameters increase with the increase in wind speed in normal operations. Moreover, platform pitch motion contributes large fluctuations in power output and generator torque in high winds.
- Regarding platform motions in normal operations, the extreme sway, heave, roll, pitch, and yaw motion appear at simulations with wind gusts whereas the surge motion seems to be triggered by the extreme turbulence. Based on the findings, it was correlated to the fact that the tensions in the upwind mooring line are greatly influenced by wind turbulence. This phenomenon was amplified by the nature of stall-regulated wind turbines, whose sustained rotor thrust tends to increase with the wind speed. As a result, the platform is being pushed downward and the upwind mooring line is being pulled upwards.
- By comparing the nacelle acceleration at cut-out wind speed between onshore and offshore CART system, it was observed that the acceleration of the nacelle in the y-direction has significantly decreased for offshore CART system. However, the

acceleration of the nacelle in the z-direction was found to be significantly larger for offshore system. Regarding the nacelle acceleration along the y axis for the onshore CART system, the peak energy was found to be mainly due to tower vibration. In contrast, the nacelle acceleration along y axis seems be excited by wave loads, 2P and 4P rotor harmonic frequencies, and the tower vibration for offshore system. However, the response amplitude of tower eigenfrequency was observed to be somewhat smaller than that of the onshore system and the tower vibration and nacelle acceleration have obviously reduced. As a result, tower bottom side-to-side moment has reduced for offshore CART system. Regarding the nacelle acceleration along the z axis, the largest amount of energy was found to be the wave energy range for offshore system, whereby the response amplitude is quite large. Apart from wave excitation forces, the nacelle acceleration was found to be dominated by the platform heave motion, rotor harmonic frequencies. This might be related to the coupling between platform pitch and heave motion. As a result, tower bottom fore-aft moment and tower bottom torsional moment have increased for offshore CART system.

- Load analyses for extreme situations with faults showed that the load case defining storm conditions and extreme sea states characterized by high wave greatly influence the platform motions. The extreme surge motion of 3.19 m was found to be driven by a particular case, in which no yaw misalignment was taken into account, but wind and wave misalignment of 30° was considered. The extreme pitch motion of 9.10° was observed in simulation which considers a misaligned yaw of 8° and wind-wave being colinear. Nevertheless, the pitch motion is still below the static inclination of 12° for survival conditions prescribed by DNVGL (DNV-GL-OS-C301, 2020). It was recommended to integrate a structural control system like a tuned mass damper to reduce the platform motions in storm conditions. For the onshore CART system, tower top side-to-side displacement was driven by the transient event posed by grid loss and shut down mode during EOG.
- By examining on the load response in extreme condition with worst consequences, it was observed that extreme loads of most parameters were significantly increased in the presence of floating substructure. Upon comparing the resulted extreme loads among normal operation, fault events, and fault events with worst consequences, it was found that the extreme loads of most parameters were triggered by extreme events with faults. The comparison of different load cases confirmed that the heave, pitch, and roll motions are greatly affected by wave-induced motions whereas surge, sway, and yaw motions are affected by motions in the mooring system which in turn is dominated by wind turbulence.

- As a result of the change in wind-wave misalignment, tensions in the mooring lines have changed. Consequently, platform sway, roll, and yaw motions have changed significantly. The mean platform yaw motion and standard deviation for the case with wind-wave misalignment are about 1.12 times and 1.64 times larger than that for the case in which wind and wave misalignment is not considered. The mean platform sway motion and standard deviation for the case with wind-wave misalignment are about 1.1 times and 2.07 times larger than that for the case in which wind and wave misalignment is not considered. Similarly, the mean platform roll motion and standard deviation for the case with wind-wave misalignment are about 1.14 times and 7.08 times larger than that for the case in which wind and wave misalignment is not considered.
- Similar to wind-wave misalignment, it was observed that current loads and direction can change tension in the mooring lines. As a result, there is a significant increase in the platform sway, roll, and yaw motions but a slight decrease in platform surge and pitch motions. The mean platform sway motion for the case with current loads is about 2.5 times larger than that for the case without current loads. Similarly, the mean platform roll motion for the case with current loads is about 1.83 times larger than that for the case without current loads whereas the standard deviation for the case with current loads is about 8.94 times larger than that for the case without current loads. The mean platform yaw motion and standard deviation for the case with current loads has increased as much as about 1.4 times and 2 times larger than that for the case without current loads.
- The present study considered fatigue loads from power production in normal turbulence wind and normal sea state without current. According to the results, the fatigue damage equivalent loads (DELs) were observed to be larger for high wind conditions, which is quite common for stall-regulated wind turbines. In addition to this, yawed conditions showed less influence on fatigue DELs in low winds whereas they have a significant influence on fatigue DELs in high wind conditions. This might be related to the fact that the CART wind turbine was designed with a high tip speed ratio and the aerodynamic loads vary with the change in angle of attack. Especially in the stall region, the angle of attack for yaw conditions tend to vary differently from the aligned condition. By examining the different Wöhler's exponents, it was found that the fatigue DELs for the blade computed with a lower material exponent is higher than that with a higher material exponent. The same applies to the steel components as well.

In summary, the findings from this study appear to be useful inputs to optimize the substructure design. It has highlighted the important dynamic system responses of the newly developed concept and delivered the preliminary estimates of critical design loads. The findings from this study also confirms that the investigated medium-sized wind turbine with stall regulation seems to be a viable concept.