Advanced Control of Next Generation Offshore Wind Turbines

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Abstract

Advanced turbine controls and structural dampers have the potential to significantly reduce the cost of energy (CoE) for offshore wind turbines. Progress made in these two areas on a Department of Energy (DoE) funded program is reported. A lidar-assisted control strategy, with objective to reduce component loads and increase energy capture, is developed and implemented. The controller has been tested in both simulations and on a 3MW utility-scale prototype. The controller results indicate a significant reduction in the tower fatigue loads. In a parallel effort, potential of a passive and semi-active tuned-mass damper (TMD) is evaluated to mitigate fatigue and extreme loads. Simulation results with passive and semi-active TMD indicate significant load reduction for tower and substructure for both fixed-bottom and floating wind turbines. Finally, levelized cost of energy modeling process to account for benefits of advanced controls is discussed.

1. Introduction

The United States waters have a technical potential of more than 2000 gigawatts of offshore wind resources. Department of energy has set a scenario to generate 54GW of offshore wind power by 2030 at a cost of $0.07 per kWh, with an interim target of 10GW by 2020 at $0.10 per kWh[1]. Europe has registered a significant reduction in cost of offshore wind as witnessed in recently announced commercial deals. A similar cost trend is expected to in the US, with a recent cost analysis by the National Renewable Energy Laboratory estimating costs below $100/megawatt-hour by 2025 in some areas of the US[2].

DoE funded-project "Cost of energy reduction for offshore Tension Leg Platform wind turbine systems through advanced control strategies for energy yield improvement, load mitigation and stabilization" is focused on (a) the development and integration of new paradigms in offshore wind turbine control strategies, and (b) evaluation of innovative structural damping methodologies to mitigate wave-induced loads. Our project has three ambitious objectives: increase overall yield by nearly 3%; reduce turbine capital cost by 6%; and reduce floating foundation capital cost by 13%, leading to overall Levelized Cost of Energy (LCOE) reduction of 6.5% using Advanced Controls.

The consortia for this project is formed of world renowned US research organizations, executing a 2-phase plan focused on the development and cost benchmarking of advanced control strategies and intensive validation at 3MW test units in the US as well as on the 6 MW Offshore test turbine.

The main intent of this publication is to provide a brief description and progress made so far on some of the activities in this program. Section 2 describes the development and validation via simulation and field testing of a lidar-assisted controller. The design objective of the controller is to mitigate component loads and enhance energy capture by utilizing advanced information about the wind time-profile. The simulation testing of the controller is carried out on a FAST model of a 3MW onshore wind turbine. Section 3 describes technical developments and trade-off analysis comparing passive non-linear TMD (N-TMD) and semi-active (SA-TMD) for both fixed-bottom and floating offshore wind systems. Numerical analysis of 6MW Haliade[1] wind turbine is carried out using FAST (NREL) and Orcaflex (Orcina) modeling tools. LCoE implications of advance controls and offshore wind turbines will be discussed in Section 4. The last section of the paper provides some conclusions and range of activities for tasks planned for the future.

2. LIDAR-Assisted Control

Several studies[3] have demonstrated the potential benefits of lidar for improved control of wind turbines. These studies have documented the benefits in terms of both extreme and fatigue loads, and energy capture. One of the tasks of our project is to adapt lidar-assisted control for offshore wind turbines, and quantify the resulting CoE benefit. As an initial step, we are working towards the design lidar-assisted feed-forward controllers for the ECO 100 3MW wind turbine for fatigue load mitigation in region 3, and energy capture enhancement in region 2.5[4].

Feedforward control based on a preview wind disturbance measurement provided by a nacelle-mounted Continuous-Wave (CW) light detection and ranging (lidar) system has been developed for rotor speed regulation and rotor thrust related loads mitigation. Another goal of this project is to validate the lidar-assisted feedforward controller performance through field testing on the 3 MW ECO 110 wind turbine located at the National Renewable Energy Laboratory (NREL)'s National Wind Technology Center (NWTC) in Golden, CO, United States.

A nacelle-mounted CW lidar system was utilized for this research. As shown in Figure 1, there is one lidar beam scanning a circle in front of the turbine, and the lidar system continuously measures the wind speed within specified conical volumes by focusing the laser beam at the centers of those volumes.

[1] Haliade is a Trademark of General Electric Company

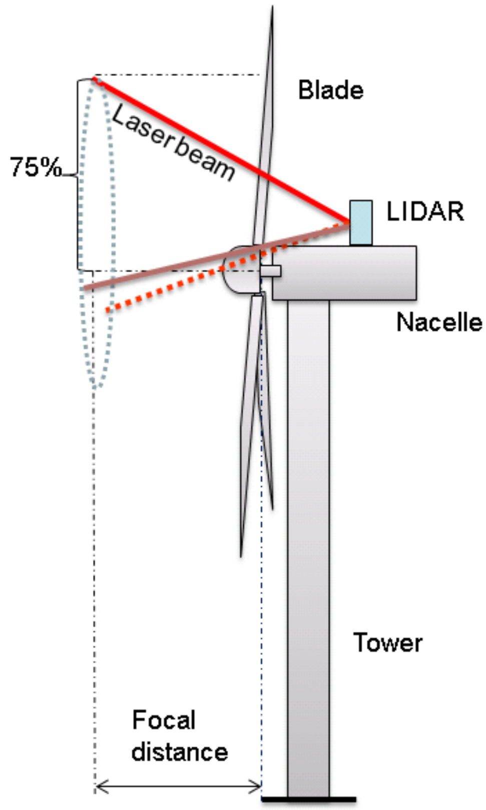


Figure 1 – LIDAR setup and measurement plane with respect to wind turbine

Existing commercial wind turbine control algorithms are typically feedback only. A drawback of the feedback only based wind turbine control is that the control actions must be determined after the wind disturbance acts on the wind turbine. Such delayed control actions would cause large rotor speed variations and degrade the rotor thrust related loadings on the turbine. To address the delay, a feedforward control with a preview wind disturbance measurement has been developed in the report.

Figure 2 and 3 depict results from using lidar-based feedforward controls in FAST simulations and field testing. The results show percentage change in damage equivalent loads (DEL) between baseline and advanced controls.

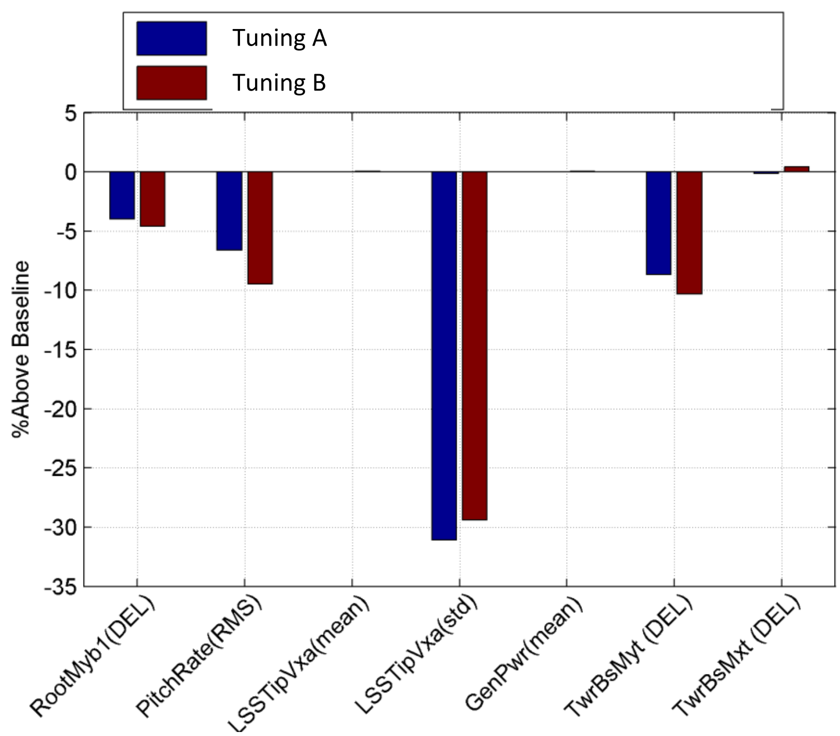


Figure 2: Performance of two versions of feedforward control compared to baseline control in FAST simulations. Up to 30% reduction in rotor speed standard deviation and 10% reduction in fore-aft tower base bending moment loads is seen.

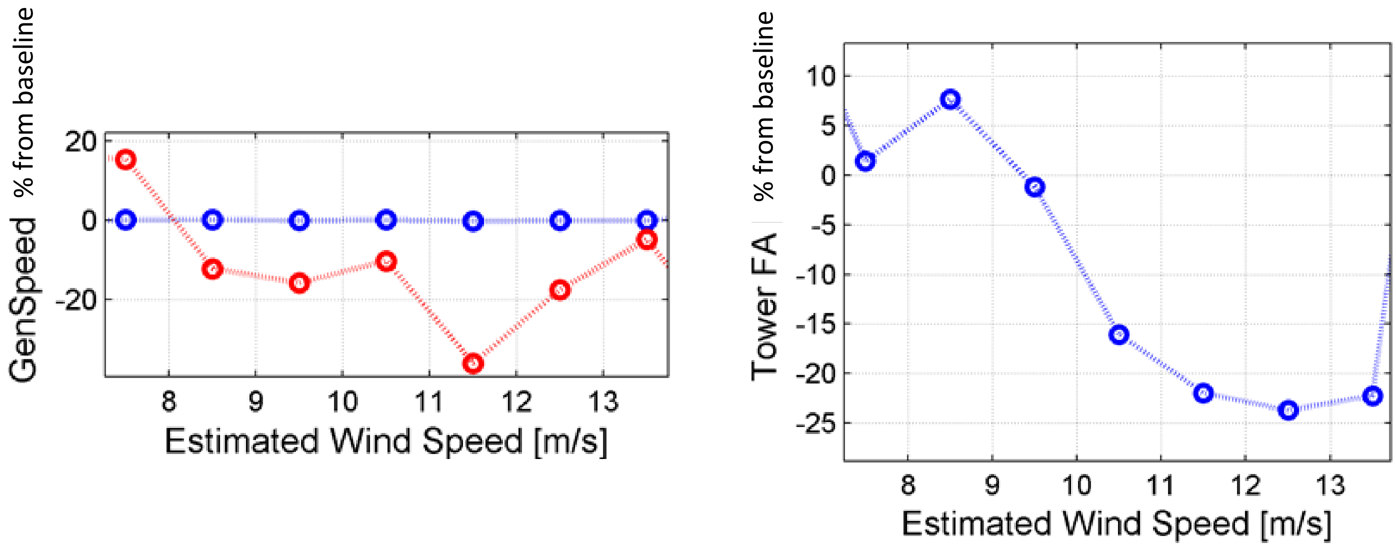


Figure 3 – Performance of feedforward control compared to baseline control in field testing with 3MW utility-scape wind turbine. Left: mean generator speed percentage change (blue) and standard deviation of generator speed percentage change (red). Right: Percentage change in tower base fore-aft moment.

3. TMD Design and Results

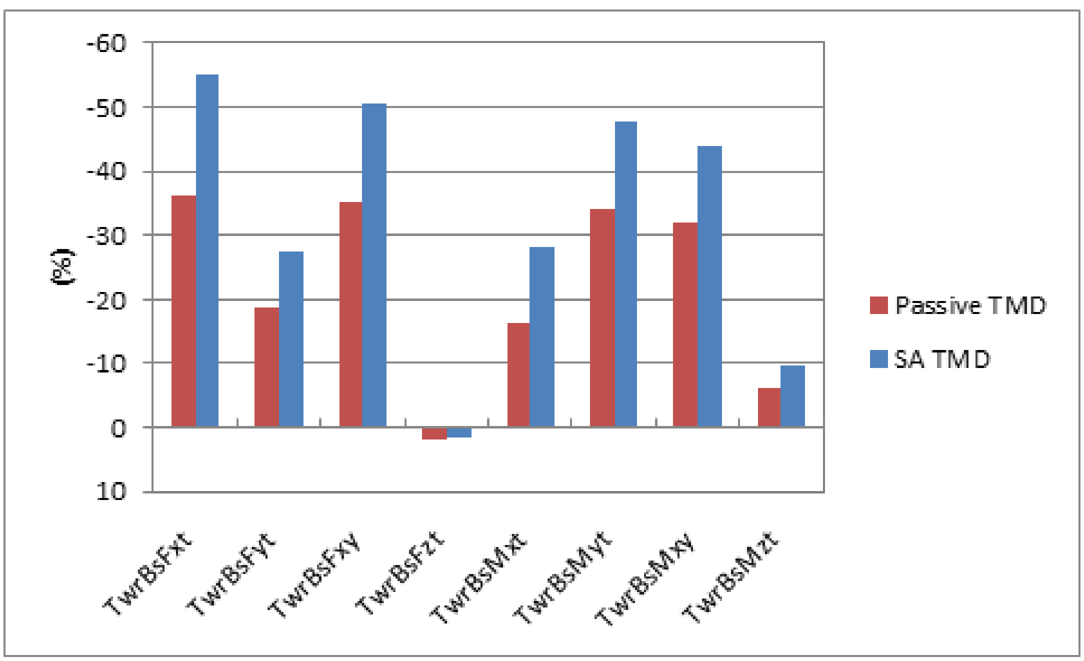
Deep water Monopile (37m) and shallow water TLP (55m) have been considered as the two candidates to verify the benefit of reducing unwanted loads and system response.

- Monopile System Response:

Design of monopoles is affected by a number of factors including: a) wind loads,(ii) wave loads, (iii) dynamic response of integrated system (e.g., eigen-frequencies of bending modes). These requirements are generally met by varying tower and monopile dimensions (wall thickness, diameter), and varying penetration of monopiles below the mudline.

Figure 4 – GE Haliade150-6MW wind turbine on a Monopile and 1st bending Side-to-Side mode in a Monopile fixed-bottom substructure[5]

For extreme loads, passive TMD leads to tower base loads reduction of 33% whereas SA-TMD results in a reduction of 44%. Moreover SA-TMD reduces the excursions of the TMD. TMD effectiveness increases for SA-TMD case vs Passive-TMD under extreme events as seen in Figure 5. On the other hand, both Passive-TMD and SA-TMD reduce fatigue loads in the side-to-side direction as seen in Figure 6.



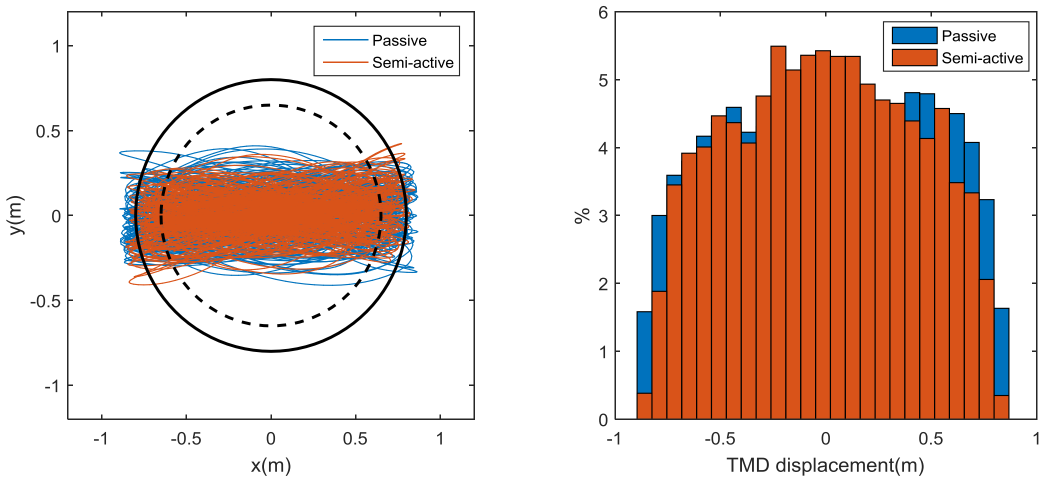


Figure 5 – Monopile Extreme load reductions and TMD excursions.

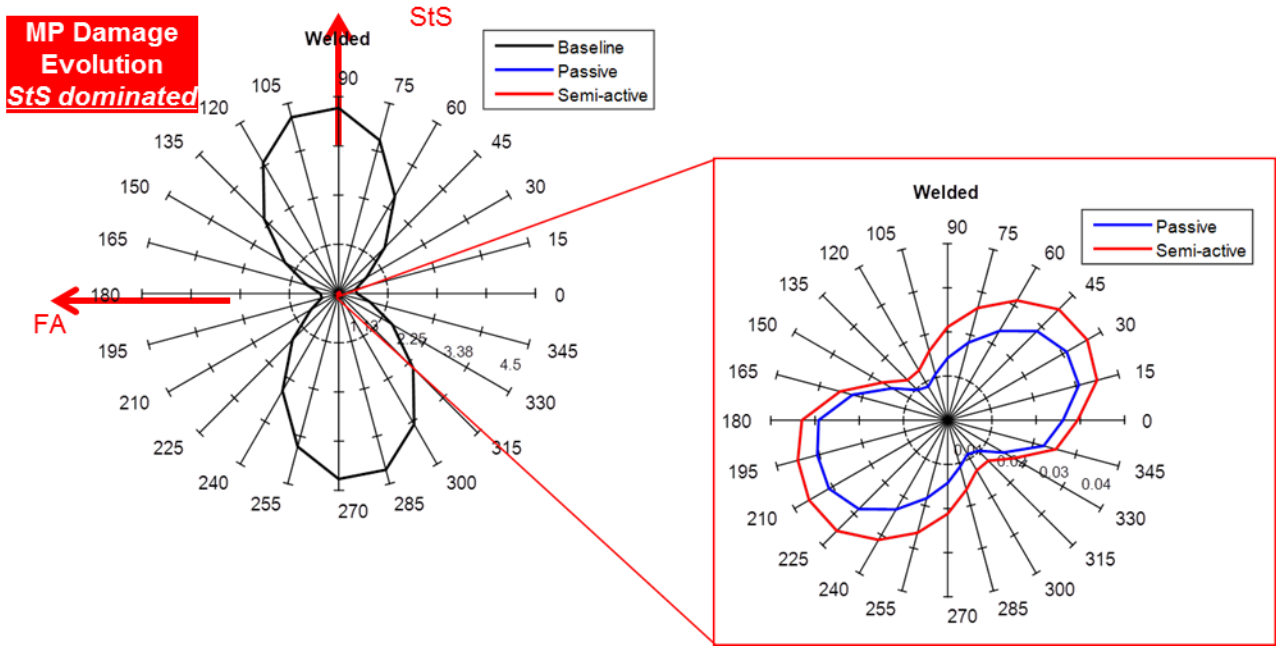
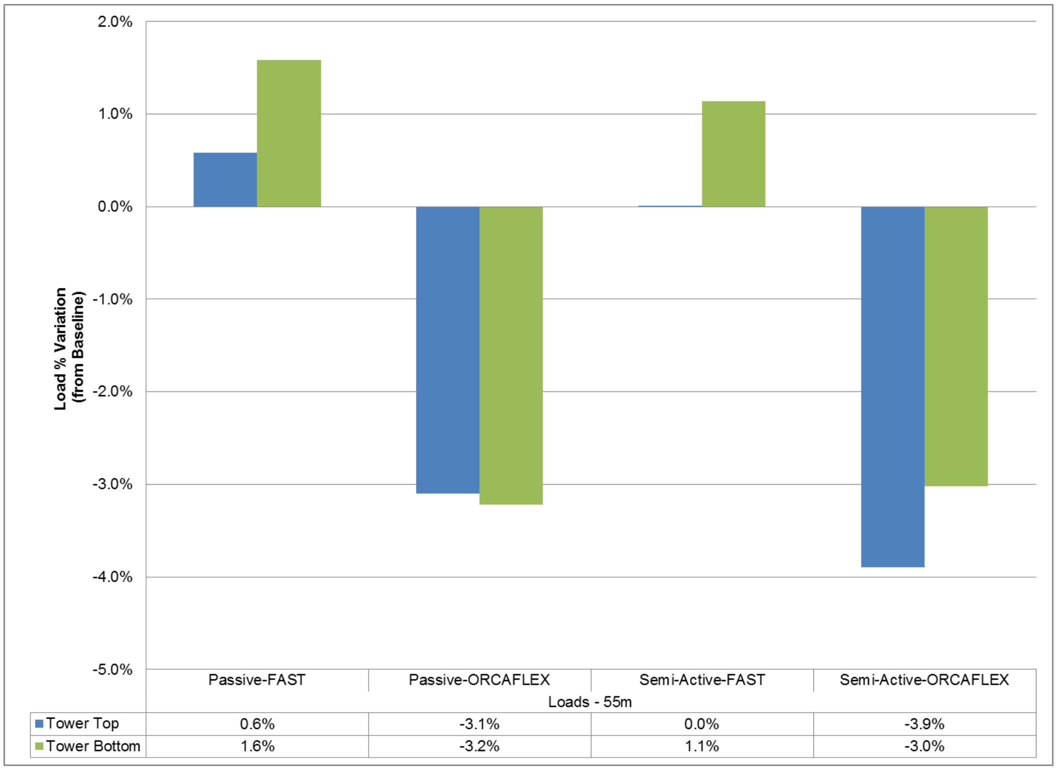


Figure 6 – Monopile Fatigue damage reductions. Passive-TMD reduces Mx by 69% & SA-TMD reduces 66% compared to the baseline scenario.

- TLP System Response:

TLP driven is driven by extreme wind & wave loads, system frequencies on top of wave spectrum, and slack line events. For deeper waters (e.g., greater than 75m), design is dominated is also dominated by wind loads current induced vortex effects. For extreme loads, TMD effectiveness was assessed using both higher fidelity Orcaflex code and a FAST model which uses linear representation for hydrodynamic effects. Extreme event load results are shown in Figure 7 for both Passive-TMD and SA-TMD. Fatigue loads are shown in in Figure 8.



	Passive-FAST	Passive-ORCAFLEX	Semi-Active-FAST	Semi-Active-ORCAFLEX
Tower Top	0.6%	-3.1%	0.0%	-3.9%
Tower Bottom	1.6%	-3.2%	1.1%	-3.0%

Figure 7 – TLP extreme load reductions.

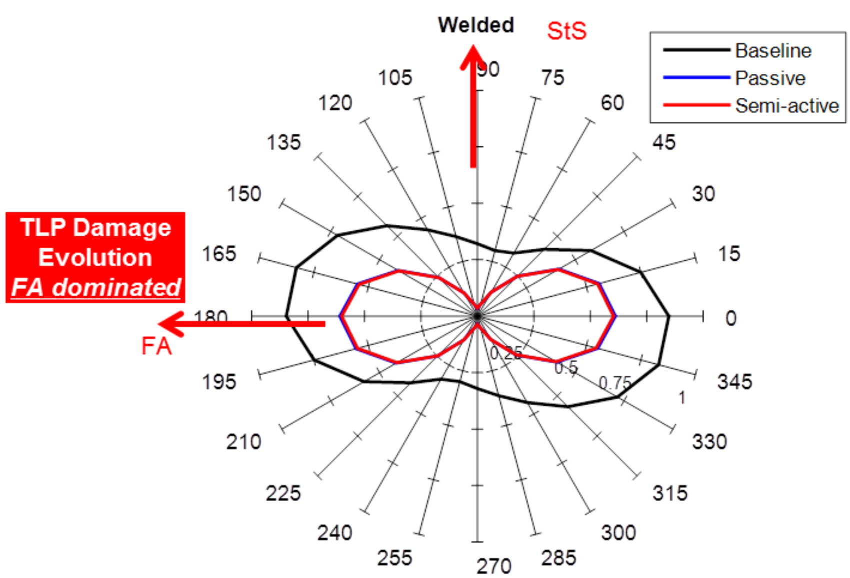


Figure 8 – TLP Fatigue damage reductions Tower Base m=3 DEL's for Passive-TMD reduces My 10% & SA-TMD reduces 11% from Baseline.

4. CoE modeling

For CoE analysis of the floating design, Haliade 150-6MW wind turbine on a TLP is considered. For the floating turbine, a candidate site location in Gulf of Maine at a distance of 55km from the shore, and 100m water depth is considered.

The LCoE model uses the template developed by NREL[6], with inputs from various industrial as well as published resources. The key components of LCoE include, among others, a) turbine capital cost including the costs of wind turbine, support-structure, and electrical infrastructure, b) development costs such as permitting and site assessment, c) installation costs including port and staging, transportation and installation of the turbine, support structure, and electrical infrastructure, and d) annual energy production obtained via taking into account the wind resources and power curve of the wind turbine.

5. Conclusions and next steps

A few of the main goals and activities of the DoE-funded project on advanced control of floating offshore wind turbines for reduction of LCoE are presented. The initial results with lidar-assisted feedforward control are discussed. Significant fatigue load reduction in region 3, are obtained based on these results. The performance of both a deep water fixed-bottom Monopile and shallow water TLP have been analyzed successfully while employing a passive TMD and semi-active TMD dampers. The use of structural damping devices reduced the extreme loads in the monopile more effectively than in the shallow water TLP, due to nature of the dynamic response and also the environmental conditions to which both systems were exposed. For fatigue loads the structural damping devices performed more effectively in the monopile than in TLP, while being activated less time compared to TLP's. On the other hand, the structural damping devices in both the monopile and the TLP contribute to a robust and reliable design, by reducing large damage values in side-to-side direction.

The CoE model will enable a systematic comparison of floating wind turbine on a TLP equipped with advanced controls against an offshore wind turbine on fixed foundation with standard controls. A key near-term future goal of this project is to test a subset of these advanced control methodologies on an offshore wind turbine. Lastly, the loads and energy capture benefits will be translated to the cost reduction via the developed LCoE model.

6. Acknowledgements

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7. References

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[1] http://www.nrel.gov/docs/fy10osti/49229.pdf

[2] http://energy.gov/sites/prod/files/2016/09/f33/National-Offshore-Wind-Strategy-report-09082016.pdf

[3] See for example http://www.ifb.uni-stuttgart.de/en/forschung/windenergie/research-projects/296-lidarswe for a good review of literature on role of LIDAR in wind turbine control.

[4] Region 2.5 is defined as the wind speed range for which generator speed is at the rated generator speed, and generator torque is below the rated generated torque.

5 Mark L. Brodersen, 2014

[6] http://www.nrel.gov/wind/windpact.html