ABSTRACT
Wind turbine technology has developed tremendously in the last decade resulting in the installation of large turbines with rated power generation of more than 5 MW. Such units with hub heights of more than 90 m and the rotor diameter of more 120 m or more require careful study of support structures. Bottom-supported structures can be designed cost effectively in relatively shallow water but the cost economics can be challenging at water depths of about 50 m in relatively harsh environments. This paper describes conceptual design of a positively buoyant Tension Leg Wind Turbine (TLWT) facility suitable for both moderate and deep water. It is competitive with bottom-supported structures in moderate water depths of 40 to 50 m based on both fabrication and installation costs. The added advantage of the TLWT design is that floating structure design is largely unaffected by the water depth. The design incorporates adequate positive buoyancy so that only the magnitude of ballast is modified to account for the weight of tether lengths at different water depths.

In addition to the description of the design, wind turbine characteristics incorporated into design, description of design details, fabrication and installation options as well as applied ocean environment loads affecting the design of tethering system and the overall fabricated and installed costs are presented for both 50 and 100 m water depth sites.

KEY WORDS: Offshore wind turbine, positively floating platform, heave restrained, Tension Leg Wind Turbine (TLWT).

INTRODUCTION
Wind Turbine Dynamics
The dynamic behavior of an offshore wind turbine on a bottom-supported structure is a complex subject requiring investigation of rotor blade and tower properties together with wind, wave and current excitation loads to minimize structural resonance. Froye and Dahlhaug (2011) provide a comprehensive discussion on rotor design and Jafri et al (2011) document the results of Monopod-based offshore wind turbine dynamics based on analytical and finite element modeling. Dynamic analysis of wind turbines on floating structures require coupled analysis of rotor, tower and support structure systems. Zambrano et al (2006) discuss dynamic modeling of a semisubmersible-based wind turbine. Numerical time-domain investigations on the dynamic behavior applicable to vertically tensioned platform (Jagdale and Ma, 2010) illustrate a practical simulation of motions. Cordle and Jonkman (2011) present survey of floating wind turbine design tools and discuss several tools suitable for coupled time-domain dynamic analysis. Jonkman (2007) also discuss the publicly available FAST code largely developed by himself at the National Renewable Energy Laboratory (NREL) applicable not only for bottom-supported wind turbines but also for the coupled dynamic analysis of floating wind turbines.

Tension Leg Wind Turbine (TLWT)
The conceptual design of TLWT presented in this paper represents the first loop of a design spiral intended for the development of a viable support structure configuration for the wind turbine system. OC3-HYWIND data on hub height, rotor/nacelle mass and tower mass reported by Myhr et al (2011) was used to model the nacelle and the tower. The model, made up of nacelle, tower, floating support structure and the tethers were analyzed for a range of parameter including floating structure diameters, drafts, inclination angles, tether locations and properties and the pretension magnitudes suitable for a location offshore California. This paper does not address wind turbine design and does not present coupled time-domain analysis. A more comprehensive coupled dynamic analysis utilizing FAST code is intended for the next phase of conceptual design.

Conceptual design presented incorporates the results of some of the developments previously introduced by International Design, Engineering and Analysis Services (I.D.E.A.S.), Inc. The TLWT is a positively buoyant structure consisting of three inclined water-piercing columns that support the vertical tower together with the nacelle and the rotor, and the restraining leg system consisting of three pretensioned vertical and three inclined tethers connect the floating structure to the sea floor (Figure 1). A TLWT is somewhat similar to a standard tension leg system as it is heave, pitch and roll-restrained. In addition, it is largely restrained in surge, sway and yaw due to its inclined non-pretensioned restraining system. Vertical tethering alone is quite adequate for a TLWT at a deepwater site. However, in relatively shallow water an appreciable set down due to combined wind, wave drift and current loading may not be acceptable, requiring lateral restraint.

Inclined columns preclude the lock-in effect of vortex-induced motions. Generated power is transferred through a cable extending from the base of the tower to the seafloor and restricted heave motions minimize potential cable fatigue damage at the interface.

The TLWT structure is made up of simple cylindrical shells with ring stiffeners and does not have complex structural joints. This simplicity of design facilitates simplicity in fabrication and installation. Parallel construction and simple details shorten construction schedule. The TLWT structure is constructed on its side and towed as a self-floater together with the tower. At the installation site the lower compartments are ballasted, tethers connected to either the preinstalled suction piles or the gravity anchors at the seafloor and the structure is brought into upright position upon further ballasting. Equal amount of water is deballasted from each column to provide the vertical tethers with the desirable site-specific pretension. A crane barge will be required to install the rotors.

396