AIAA SciTech
5-9 January 2015, Kissimmee, Florida
33rd Wind Energy Symposium
2015-1661

Downwind Pre-Aligned Rotor for a 13.2 MW Wind Turbine

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To alleviate the mass-scaling issues associated with conventional upwind rotors of extreme-scale turbines, a downwind rotor concept is considered that uses coning and curvature to align the non-circumferential loads for a given steady-state condition. This alignment can be pre-set to eliminate downwind blade moments for a given steady-state condition near rated wind speed and to minimize them for other conditions. The alleviation in downwind cantilever loads may enable a reduced structural blade mass as compared with a conventional upwind rotor. Previous quasi-steady scaling analysis indicates that this cantilever load alleviation becomes significant for extreme-scale systems (10-20 MW). To examine the potential impact of this design, Finite Element Analysis (FEA) was conducted for a 13.2 MW rated turbine at steady-state conditions for two rotor configurations with similar power outputs: 1) a conventional upwind rotor with three blades and 2) a downwind pre-aligned rotor (DPAR) with two blades. Based on previous work, the pre-aligned rotor configuration was set based on steady-state loads at a wind speed equal to 1.25 times the rated wind speed. By keeping the blade mass about the same between these two configurations, the rotor mass was reduced by approximately one third for the DPAR configuration. In addition, the average stresses on the blades for a variety of steady-state wind speeds was reduced for the DPAR configuration. However, these results can only be considered to be qualitative in terms of impact on turbine mass and cost. In particular, simulations at non-ideal, extreme and unsteady conditions are needed to determine the viability of this concept.

I. Conventional Wind Turbines

As turbine sizes have increased in the past few decades, so too have rotor masses (Fig. 1). One of the most significant design/cost challenges associated with extreme-scale systems is limiting blade mass. The rotor blade mass is used to provide the structural integrity required to resist the imposed blade loads. In particular, the structural design must avoid peak material stresses and fatigue loading at all expected operating conditions, as these can result in loss of structural performance or even blade failure. In resisting these loads, conventional upwind rotors must also be structurally stiff to limit flexibility so that the blades do not bend downstream and cause a tower strike. These requirements on structural integrity and rotor stiffness lead to large blade masses and difficult design challenges [1]. This rapid increase in rotor mass with system size is important because the rotor accounts for up to 23% of the initial total system cost (less so for off-shore turbines) and many other components of the turbine system increase in scale and cost as the rotor mass increases [2]. These costs lead directly into Cost of Energy (COE), and it is therefore crucial to minimize blade mass while maintaining performance. As such, concepts to dramatically

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reduce blade mass while maintaining aerodynamic performance, minimizing maintenance, and preventing fatigue are expected to drive future rotor design.

To address the blade mass issues associated with extreme-scale systems, a downwind rotor is proposed herein which uses a fixed downstream curvature based on force alignment near rated conditions. A rendering of this Downwind Pre-Aligned Rotor (DPAR) concept as compared with a conventional rotor is shown in Fig. 2. This concept was previously introduced by Loth *et al*. [3] and defined as a downwind "pre-aligned" rotor since the rotor is only aligned at one specific condition. For this pre-aligned speed, the combination of coning and curvature is set so as to specifically eliminate cantilever loads in the downwind direction as shown in Fig. 3. This alignment does not impact the smaller torque-wise cantilever loads as these are determined by the aerodynamic extracted power. By setting the pre-alignment speed to be close to the rated conditions, these moments can be greatly reduced for a range of wind speeds. This lessens the downwind cantilever moments, which reduces the structural mass required to withstand them. The associated reduction in the structural requirements may allow for a substantially reduced structural rotor mass. This mass savings can be substantial because the downwind cantilever loads are generally much larger than the torque-wise cantilever loads. However, quantifying these savings through blade redesign is difficult because there are many constraints that determine the structural design of a rotor blade, e.g. the parked conditions for an extreme wind. The objective of the current paper is to evaluate this concept for a 13.2 MW system at steady-state conditions in terms of: a) the potential mass savings without sacrificing resilience in parked conditions and b) the impact on the resulting structural stresses.

II. Downwind Pre-Aligned Rotor Design

For the conventional rotor, the Sandia 100 meter blade geometry was based on a 13.2 wind turbine [4]. This 100 meter blade design included a mass of 114,172 kg, designed for a rated wind speed of 11.3 m/s and a rated rotation rate of 7.44 RPM. The aerodynamic blade geometry and simplified structural layout was scaled up from the National Renewable Energy Laboratory (NREL) offshore 5 MW wind turbine [5]. In particular, the connection between the hub and the blade is modeled as a cylinder, which transitions between 15% and 19% of the blade length into a 40.5%-thick, Delft University DU99-W-405 airfoil. From 21% to 65% blade length, the airfoil transitions from the DU99-W-405 to the DU93-W-210. Thereafter, it transitions to the NACA 64-618 for the rest of the blade length. The chord distribution has a maximum chord length at approximately 25% of the blade length.

To compare with the above conventional upwind rotor, a downwind pre-aligned rotor was designed with approximately the same radius and mass per blade and the same aerodynamic geometry. The pre-alignment speed was set as 1.25 times the rated speed based on [3], and this resulted in a net downwind coning angle of 17.2^o ^{o} relative to the vertical hub plane) on top of an additional 4^o of downwind blade curvature over the length of the blade. Because of the curvature and coning, the DPAR blade length was increased to 112.7 m (including hub radius) as compared to the conventional blade length of 102.5 m (including hub radius). As described below, this lengthening was employed to ensure that the pre-aligned rotor produced the same power as the conventional rotor. For DPAR, the blade curvature was described using four discrete radial elements so that each segment allowed load-alignment, i.e. no net downwind cantilever moments. In order to consider a mass reduction of 33%, the downwind rotor was designed to have only two blades, with the weight per blade fixed to equal that of the conventional blades. Furthermore, the blade structural design was kept approximately equal so that the amount of downwind deflection at cut-out conditions was roughly equal. This choice of keeping blade geometry and mass fixed was driven by an effort to retain structural resistance in "parked" conditions in an extreme wind, e.g. hurricane. In particular, the DPAR and the conventional rotors have approximately the same blade structure and same aerodynamic frontal area, and so should similarly meet the same requirements for such extreme parked loads. This was important, as the parked condition was one the most stringent criterion for the blade design [4].

The change from three blades to two blades for the DPAR configuration reduced the rotor solidity by one-third since each blade retained the same geometry and size. This solidity change necessitated that the tip-speed ratio at rated conditions be revised in order to optimize the power output. To examine the aerodynamic influence of the blade number change, the code WT_Perf [5] was employed to determine the influence of tip speed ratio (λ) on the aerodynamic power coefficient (C_P). The results without taking into account coning and curvature effects are shown in Fig. 4 for the conventional and DPAR cases. In general, the two-bladed aspect of the DPAR design requires a higher tip speed than for the conventional three-bladed rotor in order to achieve the maximum power coefficient. In particular, the maximum C_P occurred at a tip speed ratio of 7.55 with zero pitch for the 3-bladed rotor but at a tip speed ratio of 7.85 with -1.8^o pitch for the 2-bladed rotor. The rated tip speed ratio was set to be at a slightly reduced tip speed ratio in each case to help lower the tip-speed and loads, with the conventional rotor rated tip speed set as 7.1 and the DPAR tip speed ratio set as 8.7. Comparing the rated power coefficients for these two configurations resulted in a reduction of 3.7% due to the change from three blades to two blades. The DPAR configuration was also predicted to have a further 2.5% loss in power coefficient due to the effects of coning and bade curvature [6]. To counteract this net 6% reduction in C_P, a 6% increase in the DPAR disk area was set compared to that for the conventional rotor. This was achieved by a 3% increase in radius that required a 10% lengthening of the DPAR blades based on their pre-aligned downwind angle. Thus, the pre-aligned and conventional rotors were designed to have equal power at rated conditions, at a cost of a longer blade radius and higher tip speeds for the DPAR configuration but at a savings of 33% in mass.

The above changes from the conventional configuration to the DPAR configuration can also have an effect on the tower design and mass. In particular, an increased tip speed ratio of 23% (as occurs here for DPAR) will require an increased tower stiffness to increase its natural frequency by a similar amount. Typically, this is accomplished by increasing the thickness and/or diameter of the tower, which results in increased cost. However, a 33% reduced head mass (as occurs here for DPAR) will increase the tower natural frequency by about 25%, without changing the tower mass [7]. Therefore, these two competing effects on tower design are estimated to approximately cancel each other out. However, it should be noted that the DPAR system would have an increased tip velocity, which will unfortunately lead to increased acoustic noise levels, that will require addressing.

The basic structural design of the conventional blade is shown in Figs. 5a and 5b. It includes an outer shell with two shear webs (spars running down the length of the blade) and two spar caps (upper and lower reinforcements between the two shear webs). The shear webs were placed a constant distance apart, resulting in a constant-width spar cap [4]. The shear webs were located 0.5 m forward and 1 m aft of the airfoil location of maximum thickness. The thickness of the shear webs was prescribed as a constant 9 mm based on the constant thicknesses of the Sandia 100 m blade shear webs [4]. The thickness of the spar cap was chosen as a constant 56 mm. This value was set through a parametric study so as to minimize stress concentrations along the blade.

The combination of the increased aerodynamic forces (50% more power per blade was required) but decreased downwind cantilever moments (due to load alignment at the pre-aligned speed) indicated that the DPAR blade should have a modified structural design. Based on optimization while keeping blade mass constant and equal to that of the conventional blade, the DPAR shell thickness was set to have more variation: from 68 mm to 8 mm from hub to tip. Similarly, the shear web thickness was increased (relative to the conventional blade) to 20 mm. However, the spar cap thickness of the blade was generally reduced, varying from 40 mm at the hub to 30 mm at the tip. Finally, to withstand the torque-wise loads when the aerodynamic torque force and the gravitational torque force were aligned, a trailing-edge reinforcement (70 mm thick) and a third shear web (82 mm thick) were added to the trailing edge over the last 5% of the chord length (see Figure 5c). This type of additional reinforcement was used in wind turbines such as the Sandia 100 m baseline blade [4] and allows for substantially increased ability to withstand torque-wise cantilever forces. These values were determined through parametric optimization to minimize blade stresses at rated conditions.

III. Finite Element Analysis of Structural Stresses

To determine the steady-state operational stresses expected on these three blade designs, Finite Element Analysis (FEA) was used at a variety of wind speeds. The circumferential torque loading as a function of radius was estimated based on previous computational and experimental data [8, 9]. This distribution was then scaled to match the necessary torque for a power output of 13.2 MW. The downstream forces were calculated from the torque force and the local angle of attack. Using ANSYS, the centrifugal and gravitational forces were applied using inertial loading functionality while the computational mesh was created with shell elements (SHELL181). The resulting stress distributions were found to be independent of increased grid resolution to within 1% variation. While the actual wind turbine blade is often a composite of several materials, which can have anisotropic properties, homogeneous isotropic properties were assumed herein to allow a more fundamental contrast of the conventional and force-aligned designs. For simplicity, the entire blade (outer shell, spar caps, and shear webs) was modeled as a uniform material based on E-LT-5500 fiberglass [4]. The modulus of elasticity was specified as 41.8 GPa, the Poisson's ratio as 0.28, and the density as 1920 kg/m^3. The use of isotropic material properties for this analysis will over-predict the stresses as compared to a detailed non-homgoenous anistropic commercial design, but this level of over-prediction is expected to be roughly consistent for both designs so that direct comparions can be made in terms of relative quasi-steady stress levels.

The resulting Von Mises stress distributions were then computed in the sideways position ($\varphi = \pi/2$), where the stresses are largest because both gravitational and torque forces act in the torque-wise direction. The conventional blade stresses (Fig. 6) at rated conditions (where the stresses were highest) are reasonably well distributed indicating that this design efficiently uses its structural mass for the applied loads and moment. The DPAR blade stresses at the same sideways position are shown in Figs. 7 and 8 for a range of wind speeds. The results show a substantial reduction in blade stresses for all wind speeds considered herein. This is because the downwind cantilever moments (which are much larger than the torque-wise moments) have been largely eliminated with pre-alignment. It is further surprising and encouraging that despite a 33% reduction in rotor mass for the DPAR configuration, the conventional and DPAR resulted in similar levels of tip deflections. This indicates that a pre-aligned blade would have a similar degree of flexure for rated loads as that for a conventional blade, which indicates that the DPAR rotor may have similar resilience to flutter and fatigue issues.

These proof-of-concept simulations indicate that a 13.2 MW DPAR design may yield large rotor blade mass reductions while still maintaining the conventional swept area and peak stress levels of conventional rotors throughout the operating steady-state wind-speed envelope. At even higher rated power conditions, where downwind load angles are higher, the potential for blade mass savings may be greater. However, the mass savings suggested by the results herein are only qualitative since they only consider ideal steady-state wind conditions in the operating envelope. In reality, non-ideal extreme and unsteady loads are often design drivers for blade structural design to avoid excessive stresses and fatigue loads. As such, the blade mass is primarily based on non-ideal and dynamic conditions which needed to be examined before quantitative assessment and viability can be evaluated for this DPAR concept.

IV. Conclusions

The innovation proposed herein, the downwind pre-aligned rotor concept, may be used to reduce the loads at steady-state conditions, by employing downwind coning and curvature of the blades based on force alignment near rated conditions. The cone angle and downstream curvature are set (pre-aligned) at a given wind speed, herein set to be 25% greater than the rated wind speed. This curvature ensures that downstream cantilever moments (caused by aerodynamic, gravity, and centrifugal forces) are eliminated all along the blade path at the highest load conditions. This alignment also reduces the stiffness requirements compared with conventional rotor designs. To evaluate this concept, a two-bladed version was considered for comparison with a conventional three-bladed upwind version based on a 13.2 MW Sandia design.

To evaluate the stresses acting on this rotor, a quasi-steady Finite Element Analysis was conducted using a scaled NREL 10-MW baseline rotor and the Sandia 100 m blade rotor. The sideways blade orientation was considered as this produced the largest loads when gravity and torque-wise loads act in the same direction. The DPAR design at 13.2 MW rated power yields substantially reduced stresses, despite having 50% higher aerodynamic torque loads (due to having two vs. three blades). However, these stress reductions and mass savings are based on a fundamental quasi-steady analysis. Evaluations at extreme-scale conditions, non-ideal conditions, and unsteady conditions will be important to determine whether this design is feasible. In addition, the DPAR configuration will cause tower shadow effects and a higher tip speed, both of which may require additional structural stiffening of the blades. Furthermore, detailed finite element analysis with non-homogeneous materials and system-level optimization are needed for a quantitative cost evaluation of this concept.

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Figures

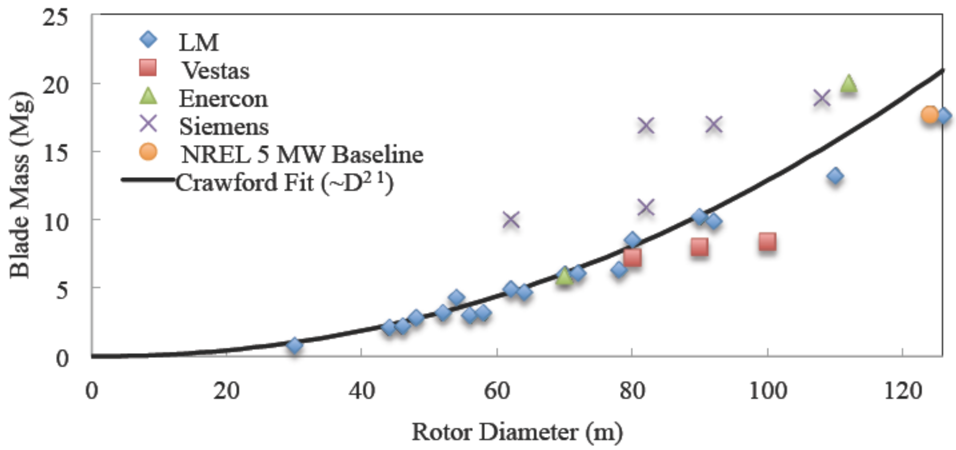


Fig. 2. Relationship between blade mass and rotor diameter.

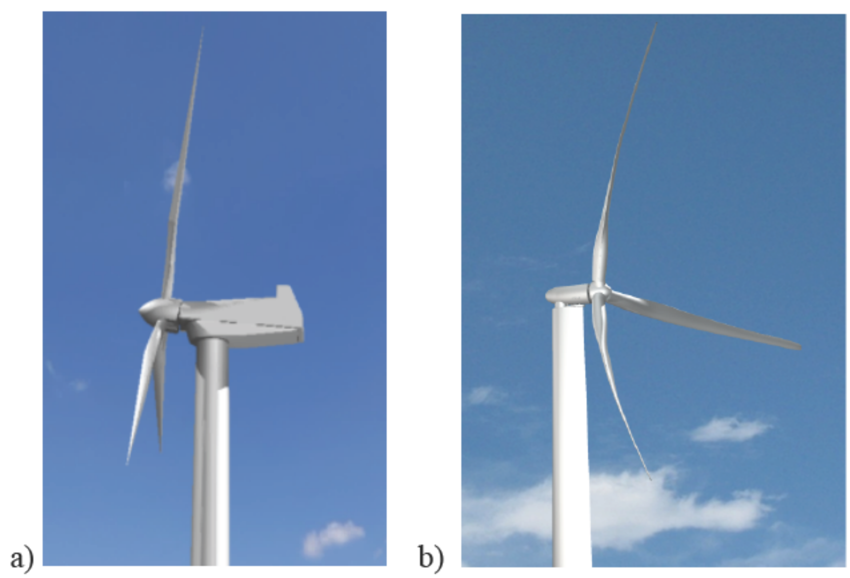
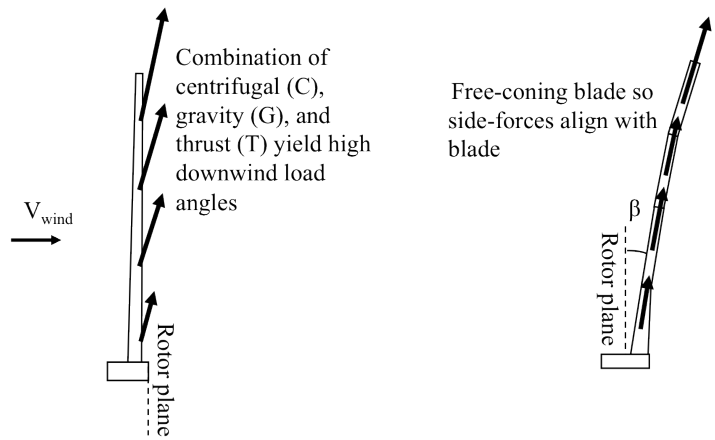


Fig. 2. Conceptual comparison of three-bladed rotors at rated conditions (wind direction is from left to right) for: a) a conventional upwind configuration, and b) a downwind pre-aligned configuration.



a) b)

Fig. 3. Distribution of forces at rated conditions with blade pointing upward for: a) a conventional upwind rotor blade and b) an aligned downwind blade that eliminates downwind cantilever hub moments.

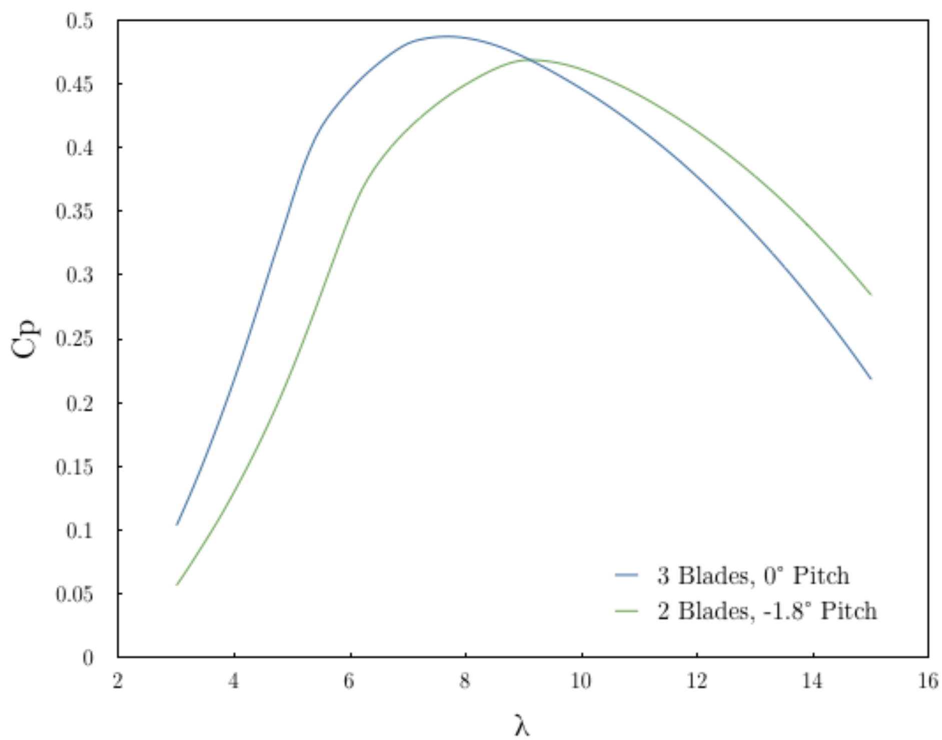


Fig. 4. WT-Perf predictions of aerodynamic power coefficient as a function of tip-speed ratio for a three-bladed Sandia 100 m blade operating with zero pitch as compared to a two-bladed system operating an optimum pitch (in terms of maximizing the aerodynamic power coefficient).

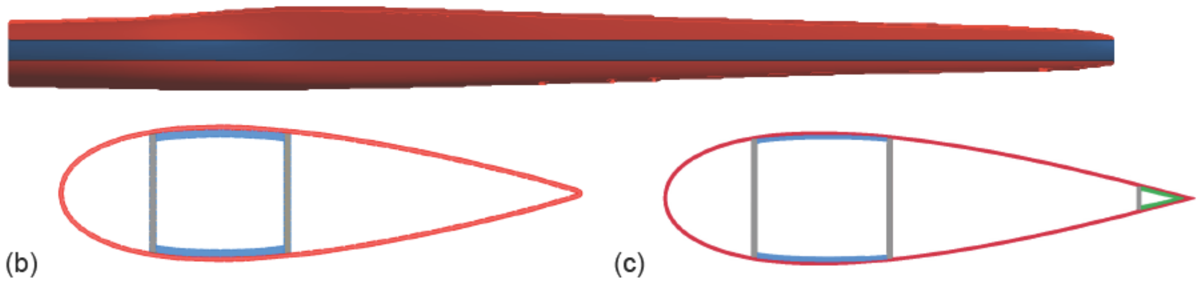


Figure 5. (a) The spar cap (blue) has a constant width based on the Sandia 100-m rotor design, (b) cross section of internal structure for the conventional blade with the spar cap (blue), shear web (grey), shell (red), and (c) the MoDaR blade which also incudes a trailing-edge reinforcement (green).

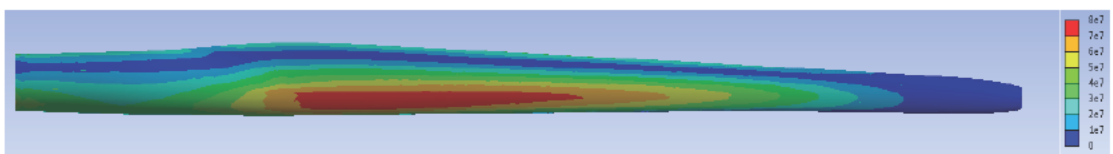


Fig. 6. Von Mises stresses in MPa along a blade for rated conditions at $\varphi = \pi/2$ for a 3-bladed conventional upwind rotor at rated wind speed.

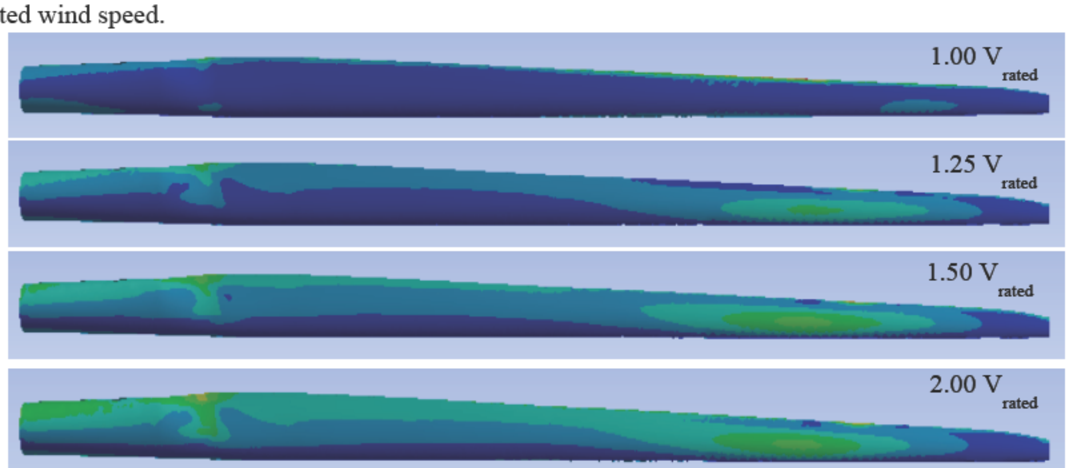


Fig. 7. Von Mises stresses along a blade for rated conditions at $\varphi = \pi/2$ for a 2-bladed downwind pre-aligned rotor at various wind speeds (same stress contours levels as Fig 6).

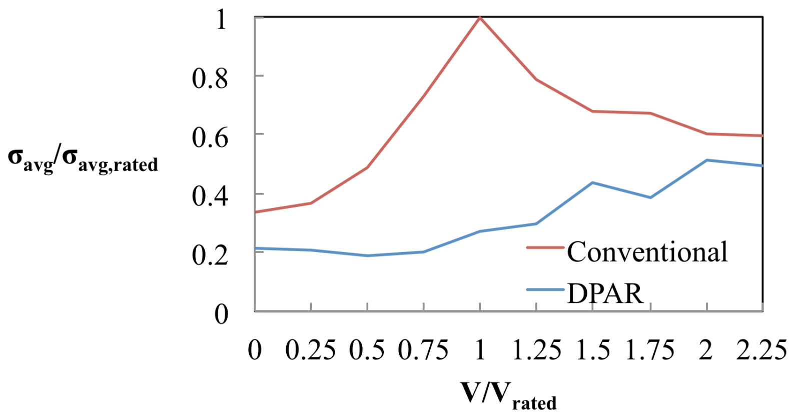


Fig. 8. Average stresses normalized by the conventional blade at rated conditions as a function of wind speed. Note that the DPAR concept uses a pre-alignment speed based $V_{align}=1.25\ V_{rated}$.