Enhanced Performance of HAWTs Using Adaptive Blades

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Abstract

As the technology for HAWT development matures, more sophisticated techniques are being examined to increase annual energy capture. One such technique envisages the use of an adaptive or "smart" blade structure that could sense the wind velocity in some fashion and accordingly modify its aerodynamic configuration to improve performance. This could be achieved in either an active or passive manner, although the passive approach is much more attractive due to its simplicity and economy. As an example, a blade design might employ elastic coupling between flapwise bending, extension and twisting so that, as it bends and extends due to the action of the aerodynamic and inertial loads, it also twists in a manner to promote stall. Because of the premature stall condition, the length of the blade could be increased without overpowering the gearbox or generator, leading to an increase in energy capture. This work encompasses a feasibility study that focuses on aerodynamic performance computations wherein the blade geometry is artificially reconfigured as a function of wind speed. These computations identify the scope of the reconfigurations required for a 5-10 per cent increase in annual energy capture. Results show that increases of this magnitude can be achieved with a modest amount of blade twist (2 degrees). Follow-on work will investigate the design achievability of these reconfigurations and methods for fabricating selected concepts.

Introduction

The concept of building blades that adapt to the incident wind loading is not new. Many blade concepts that twist to change their angle of attack in response to the thrust loading were produced in the early days of the wind energy rush of the late twentieth century with quite varied objectives and approaches. Cheney and Spierings (1978) presented a power regulation design that used a centrifugally loaded mass on an elastic arm to adjust the full span pitch. Bottrell (1981) had a design for cyclically adjusting pitch for per rev load balancing. The North Wind 4kW (Currin, 1981) had a system for passively adjustin the blade pitch for both power and load control. Hohenemser and Swift (1981) studied a design for alleviating the high loads due to yaw control by cyclic pitch adjustments. Most of the early attempts relied on pitching the blades to feather to reduce the power output and loads. Elastic deformation of turbine blades has also been documented (Stoddard, et al., 1989) with elastic twist due to normal operating loads well over two degrees noted.

Stall controlled rotors have received a shot in the arm in the past decade with the advent of designer airfoils (Klimas, 1984; Tangler and Somers, 1987) that enhance the stall regulation of a wind turbine. These airfoils have been quite successful in reducing the maximum power output of a given sized rotor allowing the rotor diameter to be increased without increasing plant capacity. The larger rotor then produces more net energy without proportional increases in system cost.

Our aim in this feasibility study is to investigate the enhanced stall approach using an adaptive blade to limit maximum power. This will enable both rotor diameter and system energy increases without proportional increases in system cost. The purpose of this study is only to investigate the potential for energy increases. The question to be answered here is "How much energy production can be gained by adaptive blades twisting to stall?" Only constant speed options are considered in this investigation.

If the energy increases prove large enough (5-10%) follow-on work will be required to first design a blade with the desired twisting characteristics, and then to identify methods for its manufacture. In the design process aeroelastic instability issues will be addressed as it is quite possible that a response to load which increases load (in the linear angle of attack range) could lead to amplified structural response.

Method of Analysis

The aerodynamic performance of various HAWT configurations was established using PROP for personal computers (Tangler,1987). The PROP family of codes is somewhat of an industry standard, and the "personal computer" version is

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relatively easy to modify due to its simplicity.

In this study a modified version of the PROP software is used in a mode wherein the turbine RPM is fixed and the windspeed is allowed to vary over a specified range, the result of interest being a power curve for the turbine. Normally for these computations the geometry of the rotor is fixed, but for this study the blade twist is prescribed as a function of windspeed and spanwise location on the blade. As an example, the tip of the blade might undergo rotations of zero to two degrees as a linear function of windspeed over a specified range, for each tip rotation, spanwise blade twist might vary linearly from 0 degrees at the hub to the tip value. The goal is to simulate blade motion that might be achieved with an adaptive blade without actually designing the blade or computing its response to the aerodynamic loads. Thus, the blade twist prescription as a function of windspeed and spanwise location is strictly an educated guess of what might be possible. If these twisting scenarios promote stall in such a way that the captured energy can be significantly increased by extending the blade length, without an increase in maximum power output, a proof of concept is established. The difficult engineering details required to bring the concept to fruition will be addressed in follow-on work.

Two options are provided for twist as a function of blade position: constant with span and linear with span. For constant twist with span, the twisting is assumed to take place locally near the hub in a specially designed blade segment. For linear twist, the blade is assumed to be designed so that under the action of the various loadings it twists in a linear fashion from the hub to the tip. It is hoped that the twisting behavior can be accomplished using strictly passive methods, but active methods may have to be pursued also.

For each of the above spanwise twisting options, two options are investigated for the manner in which the blade tip twists with windspeed: linearly and quadratically. A third option is also investigated where the blade tip twists linearly with the output power of the turbine. With these three options it is hoped that the most likely scenarios for the twisting of the blade under load are captured as the wind speed increases. The two blade twist configurations along with the three twisting schedules are implemented via modifications to the PROP software

The procedure followed in this study is first to establish a power curve for the turbine of interest with a rigid rotor (i.e. no twisting). From this curve a maximum power output is selected that should not be exceeded due to the design limitations of the turbine gearbox and generator. After selecting a maximum blade tip twist, a twisting schedule and a twist configuration the PROP performance code is run iteratively, increasing the blade length until the maximum power output matched that of the one with the rigid rotor. The blade chord was not increased proportionately with the blade length. This new power curve is output from PROP in a format readable by the MATLAB software (The Math Works Inc., 1992) for additional processing and graphical visualization.

The additional processing in MATLAB consists primarily of multiplying the power curve by a windspeed probability distribution and integrating the result to obtain annual energy estimates. A Rayleigh probability distribution which is characterized by the average windspeed at the site of interest (Equation 1) is used for this purpose. In Equation 1, V is the windspeed and $\overline{V}$ is the site average windspeed. Typical

$$f(V) = \frac{2}{V} \times \frac{\pi}{4}\left(\frac{V}{\overline{V}}\right)^2 \exp\left[-\frac{\pi}{4}\left(\frac{V}{\overline{V}}\right)^2\right] \qquad (1)$$

Rayleigh probability distributions with average windspeeds of 5.0, 6.5 and 8.0 m/s are shown in Figure 1. To determine the effect of the site average windspeed on the annual energy capture, computations are completed over a range of average windspeeds from 5.0 m/s to 8.0 m/s.

For each turbine configuration, including the rigid one, a curve for the annual energy capture versus average windspeed is computed. From these curves the new curves for the percent increase in annual energy over the untwisted configuration are obtained. Such curves are obtained for a generic utility scale turbine (~300 kw) and are presented in the next section.

Results

First a credible power curve (electric) had to be developed for the generic turbine, using available information from the National Renewable Energy Laboratory (NREL) for the blade geometry, airfoil data and drive train efficiency. The various options of the PROP software were exercised in an attempt to produce a reasonable power curve. Tangler and Smith et. al. (1991) provided valuable insight and guidance in completing this task. The electric power curve that was finally obtained is shown in Figure 2.

For the first series of variable twist rotor configurations, each blade was constrained to twist at its root only, producing a uniform incremental pitch along its length (constant twist). This action is equivalent to full blade pitch control. The maximum incremental twist permitted was set at either one degree or two degrees. For each of these twist values, the three twisting schedules (linear with windspeed, quadratic with windspeed, and linear with power) were applied to the rotor. After adjusting the blade lengths to achieve rated maximum power, new power curves were generated and are shown in Figure 3 for the two degree maximum twist case. As expected the power curves for the three twisting schedules are skewed to the left, all with a maximum power approximately equal to that of the power curve for the rigid generic turbine. The fact that the three curves deviate only slightly from one another, indicates that the schedule details may not be of great importance. Blade length increases for the three schedules are: 0.716 meters - linear with windspeed; 0.625 meters - quadratic with windspeed.; and 0.792 meters - linear with power. When compared to the original blade length of 13.106 meters, these increases are of the order of 5%.

To obtain the increase in annual energy capture as a function of the site average windspeed, these power curves were used in conjunction with Rayleigh windspeed distributions like the ones shown in Figure 1. Results for both a one degree maximum twist and a two degree maximum twist are shown in Figure 4. The lower three curves correspond to a maximum twist of one degree and the upper ones, two degrees of twist. Generally, the variation of each of the individual curves over the average windspeed range is of the order of 1% in annual energy or less, indicating that the annual energy increase is not particularly sensitive to the site average windspeed. As noted from the curves, the annual energy increase is substantial, especially for the configurations with a maximum of two degrees of twist.

For the second series of variable twist rotor configurations the blades were constrained to twist linearly with span. This action might be achieved through specially designed composite blades which are coupled in bending and/or extension, and torsion. The maximum incremental twist permitted at the tip of the blade was set at either one degree or two degrees, and the three twisting schedules were applied in each case. The new power curves that resulted from this process are shown in Figure 5 for the two degree maximum twist case. As for the constant twist series, the power curves are skewed to the left, although to a lesser degree, and they deviate only slightly from one another. Blade length increases for the three schedules are: 0.533 meters - linear with windspeed; 0.482 meters - quadratic with windspeed; and 0.579 meters - linear with power. When compared to the original blade length of 13.106 meters, these increases are of the order of 4%.

The annual energy increase versus site average windspeed, associated with these power curves is shown in Figure 6. As before, the lower three curves correspond to a maximum twist of one degree and the upper ones, two degrees of twist. As with the constant twist blades the annual energy increase for the linear twist blades is also not particularly sensitive to the site average windspeed. Although the annual energy increases for the linear twist blades is somewhat less than those for the constant twist ones, the increases are still significant.

Some final computations were completed to identify limits on the concept of promoting stall to increase annual energy capture. With the blade in a linear twist configuration on a linear twisting schedule, the annual energy increase was obtained for maximum twists of five, ten, and fifteen degrees. These were combined with the one and two degree results obtained previously and all were averaged over the range of mean windspeeds to obtain an average annual energy capture. The per cent increase in average annual energy capture over the base-line design is plotted in Figure 7 versus maximum twist. Also plotted in Figure 7 is the per cent increase in blade radius required to achieve this increase in performance. While the blade radius increases in an approximately linear fashion, diminishing returns are apparent for the increase in average annual energy capture, which peaks at a maximum twist of ten degrees

As stated previously, the blade chord was not increased proportionately with the blade length. Some trial calculations where the chord was increased proportionately yielded smaller increases in annual energy. The greater solidity resulting from the increased chord caused the blade length increases to be smaller when the maximum power limit was reached, leading to a smaller annual energy increase. The practice of increasing the blade length slightly (~5%) without increasing the chord may produce some structural and/or aeroelastic instability problems.

Conclusions and Recommendations

Using the a generic utility sized rotor as a test case, two blade twist configurations in conjunction with three twisting schedules were investigated to determine the benefits of blades that twist towards stall with applied loading. In all cases the power curves skewed to the left producing increases in annual energy of the order of 10 -15% for a maximum blade twist of two degrees and 5 -7% for a one degree maximum twist. Although the twisting schedules had marked differences, the annual energy increases differed from one another only modestly (~20%) for a given blade twist configuration. The predicted annual energy increases were not particularly sensitive to the site average windspeed over the range investigated (5 - 8 m/sec).

This study has indicated that substantial increases in annual energy capture can be achieved if the blades can be made to twist towards stall with increasing applied load. Moreover, if the maximum incremental blade twists that were used in this study can be realized, the system seems to be robust in the sense that the details of the blade twist configuration, the twisting schedule and the site average windspeed are not crucial to achieving a significant increase in annual energy capture. On this basis it is recommended that design studies be initiated to identify blade designs that could passively twist towards stall to the desired levels under the action of the applied loads. It is imperative that these design studies address aeroelastic instability due to the adaptive nature of the blades.

Acknowledgment

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development of a generic utility scale turbine and its associated electric power curve.

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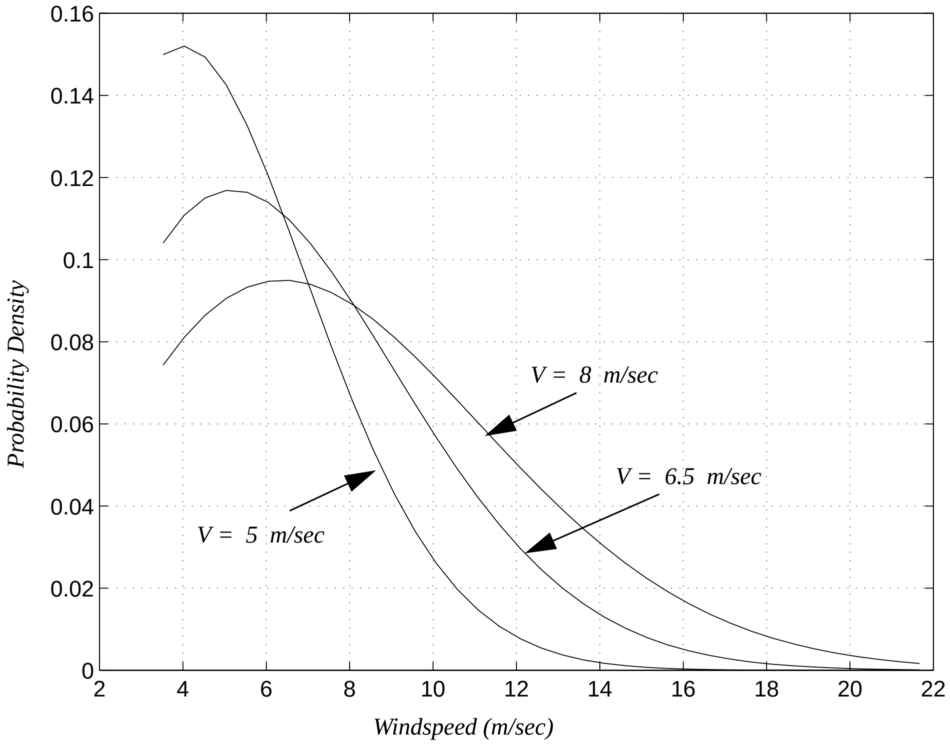

Figure 1. *Rayleigh probability distributions for windspeed with average windspeeds of 5.0, 6.5 and 8.0 m/s.*

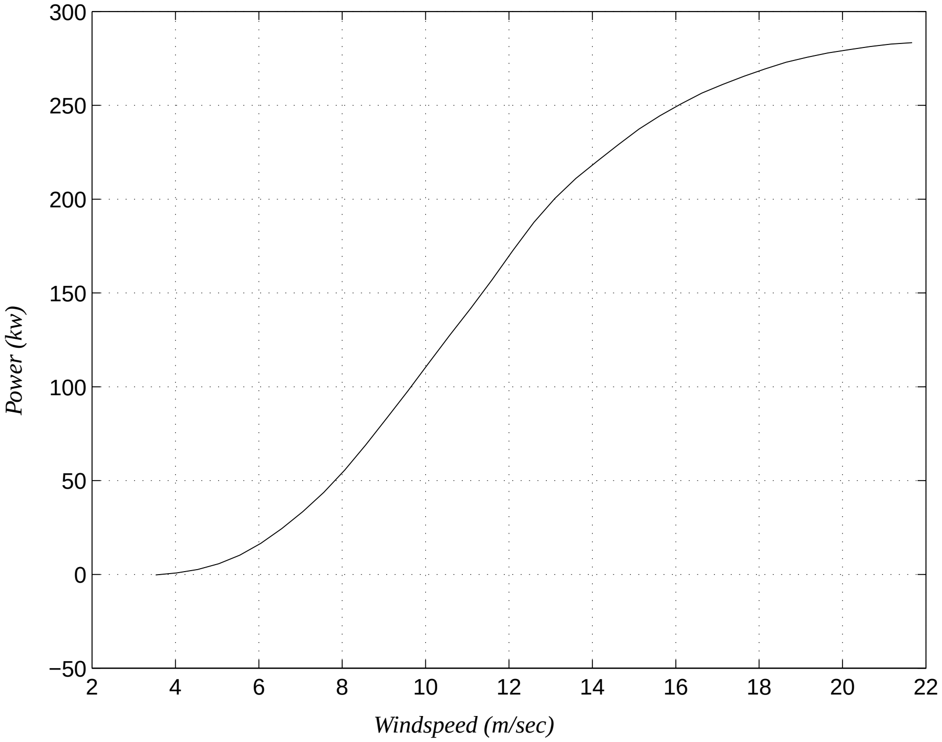

Figure 2. *Power curve for the generic rigid rotor.*

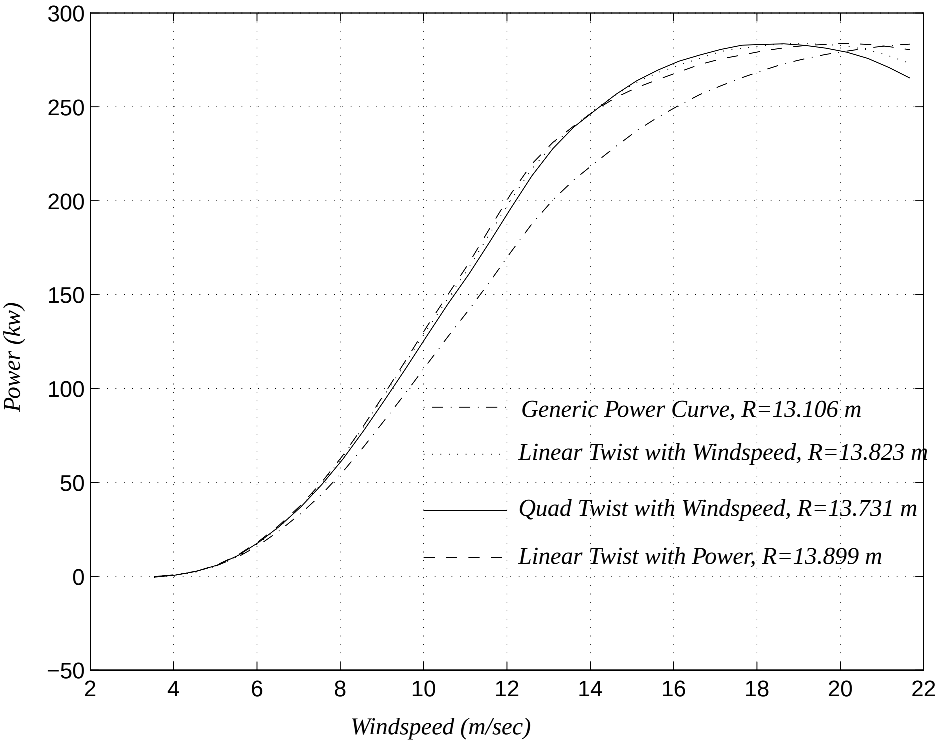

Figure 3. *Power curves for the three twisting schedules - constant twist along the span.*

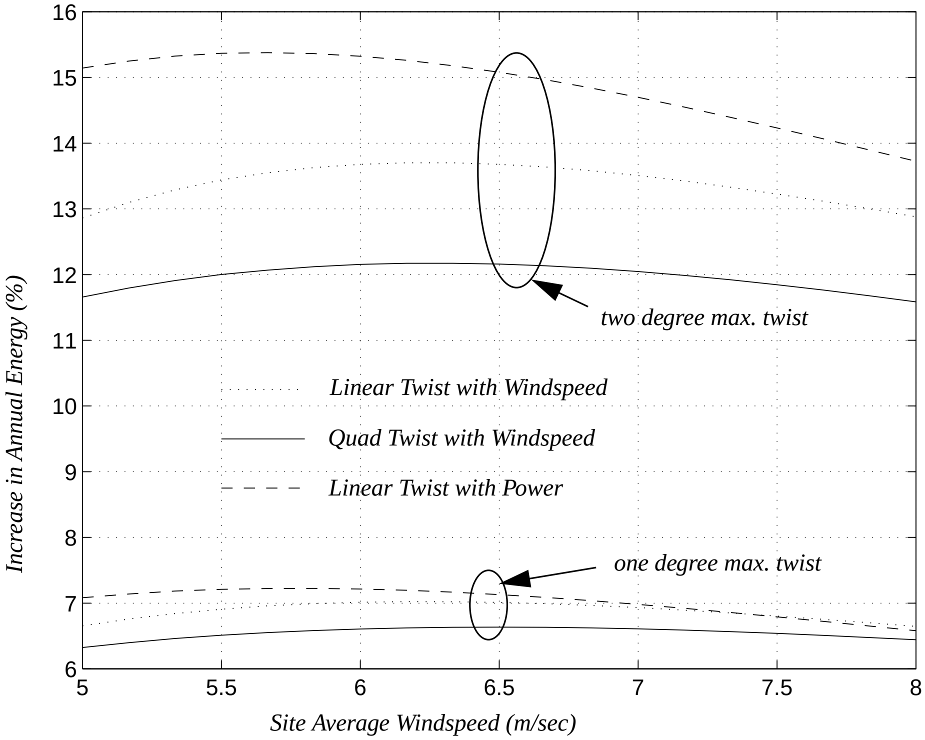

Figure 4. *Percent increase in annual energy for the three twisting schedules - constant twist along the span.*

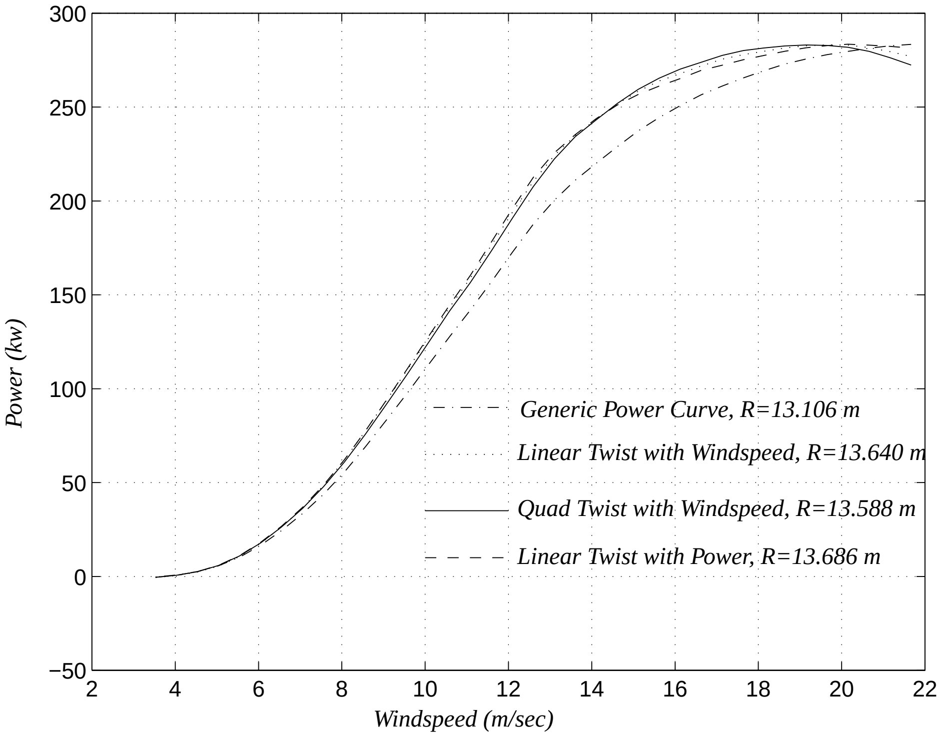

Figure 5. *Power curves for the three twisting schedules - linear twist along the span.*

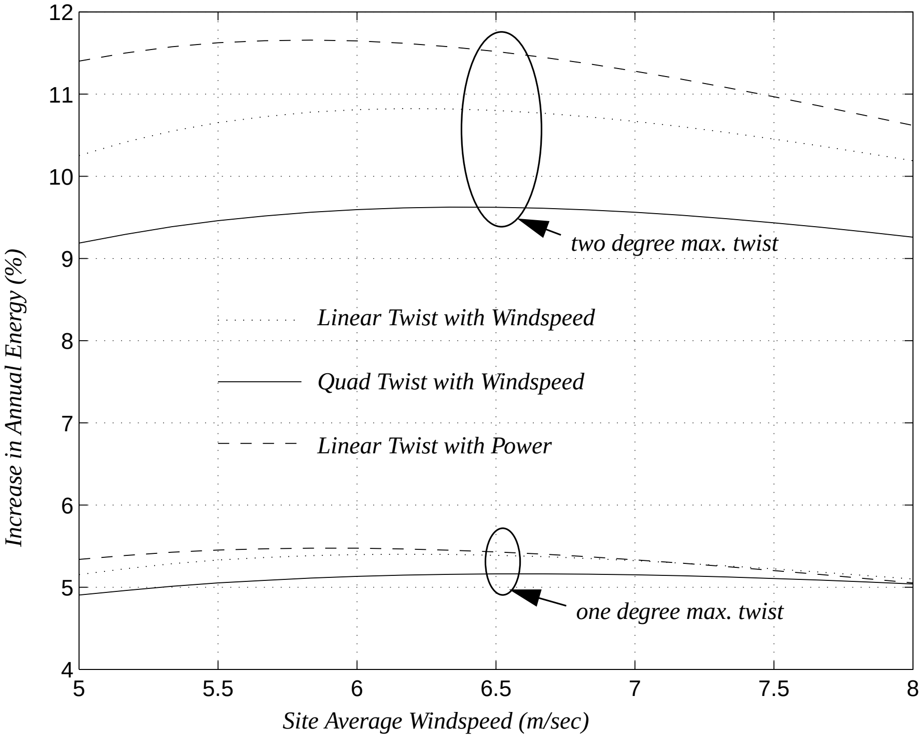

Figure 6. *Percent increase in annual energy for the three twisting schedules - linear twist along the span.*

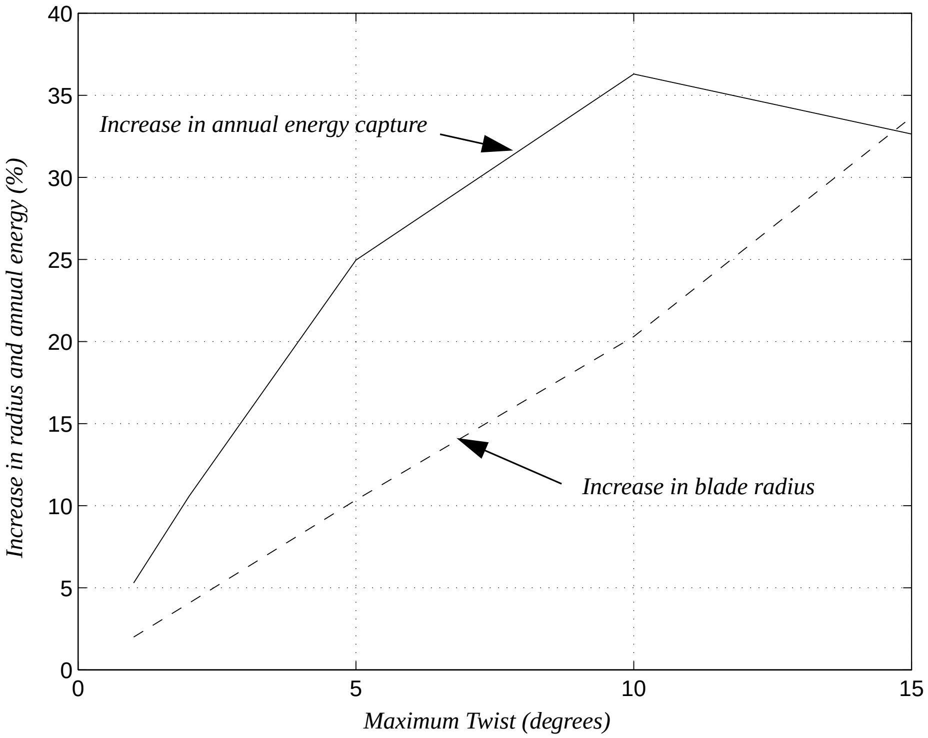

Figure 7. *Percent increase in blade radius and average annual energy capture versus maximum blade twist.*