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ABSTRACT

The Solar Energy Research Institute (SERI), in cooperation with SeaWest Energy Group, has completed extensive atmospheric testing of the special-purpose SERI thin-airfoil family during the 1990 wind season. The purpose of this test program was to experimentally verify the predicted performance characteristics of the thin-airfoil family on a geometrically optimized blade, and to compare it to original-equipment blades under atmospheric wind conditions. The tests were run on two identical Micon 65/13 horizontal-axis wind turbines installed side-by-side in a wind farm. The thin-airfoil family 7.96 m blades were installed on one turbine, and AeroStar 7.41 m blades were installed on the other. This paper presents final performance results of the side-by-side comparative field test for both clean and dirty blade conditions.

1. INTRODUCTION

The energy crisis of the 1970s led to a generation of wind turbines that helped identify numerous deficiencies in the technology. One of these deficiencies was the lack of suitable airfoils for wind turbine blades. The performance characteristics of available airfoils, which were designed for aircraft use, were found to be inadequate for wind turbines. This problem was most prominent on the stall-regulated horizontal-axis wind turbine (HAWT). Because of its simplicity and low cost, this type of turbine has become the predominant type of turbine found in the California wind farms. Airfoils chosen for this and other types of machines have centered on the half-century-old NACA 23XXX and NACA 44XX series of airfoils. The NACA 23XXX series was found to experience large drops in maximum lift coefficient (C_{lmax}) as the airfoil became soiled with insect accumulation. Peak rotor power, which is proportional to the airfoil's C_{lmax} in the tip region of the blade, would drop 30% to 50% when the annual spring hatch of insects soiled the blade's leading edge. This problem was also found on the NACA 44XX series of airfoils to a lesser degree. Both the NACA 44XX and NACA 23XXX series of airfoils have a high C_{lmax} to guard against stalling the wing of an aircraft. Tangler and Tu (1) showed the high C_{lmax} is undesirable in the tip region of stall-regulated wind turbines because it results in excessive peak power at high wind speeds. In turn, the excessive peak power leads to a reduction in generator and transmission life.

In an effort to solve the blade soiling problem, manufacturers began using the LS-1 and NACA 63XXX series of airfoils. Both of these airfoil sections have their camber farther aft which provides some improvement in reducing the airfoil's C_{lmax} sensitivity to roughness effects. In addition, the NACA 63XXX provided a lower C_{lmax}, which helps control peak power. However, this characteristic is desirable only over the tip region of the blade for a stall-regulated rotor. When the NACA 63XXX is used on the inboard portion of the blade, where a high C_{lmax} airfoil is needed, a degradation in energy production can be expected at low to medium wind speeds.

The LS-1 series has the opposite problem. This airfoil provides a desirable high C_{lmax} toward the blade root, but contributes to excessive peak power when used over the outboard portion of the blade. The excessive peak power must then be controlled with an undesirable reduction in blade solidity or a less efficient blade operating pitch angle. Although both the NACA 63XXX and LS-1 airfoils provide some improvement for roughness effects over the NACA 23XXX and NACA 44XX airfoils, further improvements were needed to lower energy cost.

The lack of airfoils with performance characteristics tailored to the needs of stall-regulated HAWTs motivated the development of SERI's thin-airfoil family (Figure 1). This airfoil design effort by Tangler and Somers (2) was completed in 1985. That same year the primary member of the airfoil family was wind tunnel tested by Somers (3) to verify its predicted two-dimensional performance characteristics. The thin-airfoil family was then integrated into the design of a geometrically optimized rotor blade by Jackson (4) for 65 kW commercial machines. To verify the predicted performance characteristics of this new blade, a side-by-side comparative atmospheric test was conducted using two Micon 65/13 wind turbines. Thin-airfoil family blades were mounted on one turbine, and standard AeroStar blades were mounted on the other. This paper presents final rotor performance results from that test, which verified the aerodynamic properties of the thin-airfoil family on a stall-regulated rotor. A subsequent paper will present results from the structural load measurements.

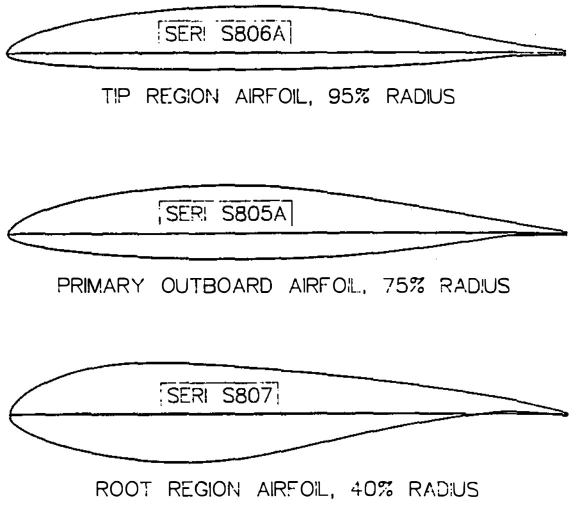

Figure 1. SERI Thin-Airfoil Family

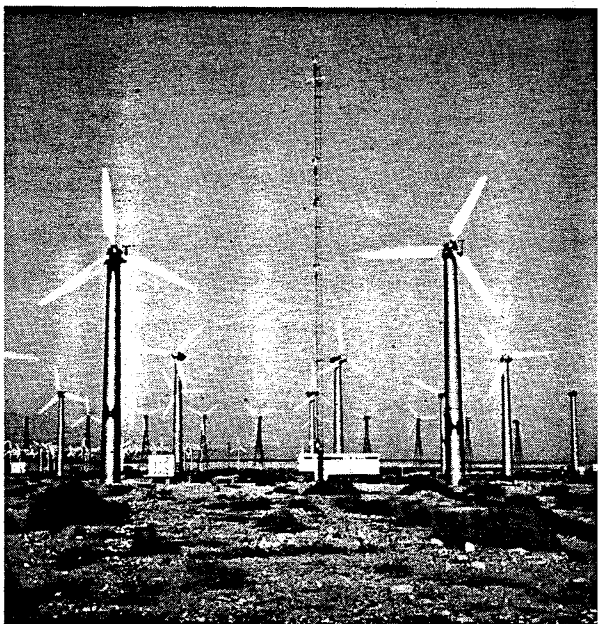

Figure 2. Side-by-Side Micon 65/13 Machines

2. TEST SETUP

The atmospheric test was conducted using two side-by-side Micon 65/13 horizontal-axis wind turbines under a cooperative agreement with SeaWest Energy Group. The machines (Figure 2) were located on flat terrain along a row perpendicular to the prevailing wind direction at SeaWest Energy Group's San Gorgonio site. The location was in the center of a group of more than 600 machines and was characterized by lower energy production and greater machine fatigue damage than in the surrounding wind park. The anemometer was located upwind, at hub height, halfway between the two machines. Data from the anemometer and each machine power transducer were routed to a data trailer located downwind between the machines. Further details on the instrumentation were reported in (5) by Tangler et al. A top-view schematic (Figure 3) illustrates the relative placement of the machines with respect to the anemometer tower.

The Micon 65/13 is an upwind, three-bladed, fixed-pitch, rigid-hub machine having an active yaw drive. It uses a 13 kW generator for low-wind-speed operation. Cut-in wind speed for the machine is 4.0 m/sec (9 mph). The machine has no shutdown wind speed and depends on the rotor blade's stall-regulating ability to control maximum power output at wind speeds greater than 13.4 m/sec (30 mph). The rotor has a hub height of 23.0 m (75 ft) and normally uses 7.41 m (24.3 ft) AeroStar blades, which result in a 16.0 m (52.5 ft) rotor diameter. With the 7.96 m (26.1 ft) SERI thin-airfoil blades, manufactured by Phoenix Industries, the rotor diameter is increased to 17.1 m (56.1 ft), which results in a 14.2% increase in projected disc area. The longer SERI blades (Figure 4) provide 3% more blade projected surface area than the AeroStar blades. A summary of each machine's characteristics is provided in Table I.

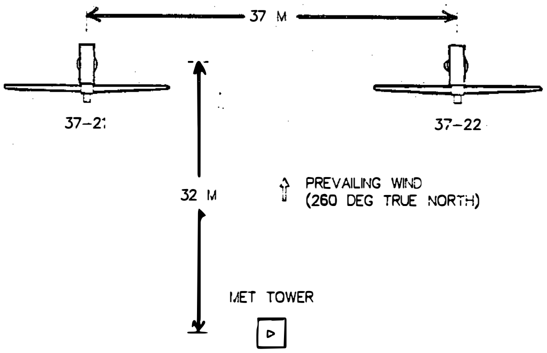

Figure 3. Wind Turbines and Meteorological Tower Layout

TABLE 1 MICON 65 CHARACTERISTICS

	AeroStar Blade	SERI Blade
Rotor Diameter	16.0 m (52.4 ft)	17.0 m (56.0 ft)
Blade Length	7.41 m (24.3 ft)	7.96 m (26.1 ft)
Airfoils	NACA 4415-24	S806A,S805A,S807
Twist	8.4° linear	20° nonlinear
Rotor Speed	48 rpm	48 rpm
Hub Height	23.0 m (75 ft)	23.0 m (75 ft)
Tilt Angle	4°	4°
Cone Angle	4°	4°
Rotor Orientation	Upwind	Upwind
Blade Material	Fiberglass-reinforced polyester	
Blade Flange	Hutter design	Steel flange
Blade Weight	800-850 lb	630 lb
First Flapwise Frequency s	4.05 hz	3.16 hz
First Edgewise s Frequency	5.80 hz	7.20 hz
Generator Type	Induction 13/65 kw	
Gearbox	Helical gear, parallel shaft	
Overspeed Control	Centrifugally activated tip brakes	

3. ROTOR PERFORMANCE COMPARISON

During the side-by-side evaluation of the SERI and AeroStar blades, power curves were established for both clean and dirty blade conditions. More than 100 hours of data were acquired for both blade conditions. Dirty blade roughness effects (Figure 5) were simulated using an upper and lower leading-edge strip of double-coated tape 5.08 cm (2 in.) wide and 0.05 mm thick, randomly scattered with grit. The tape

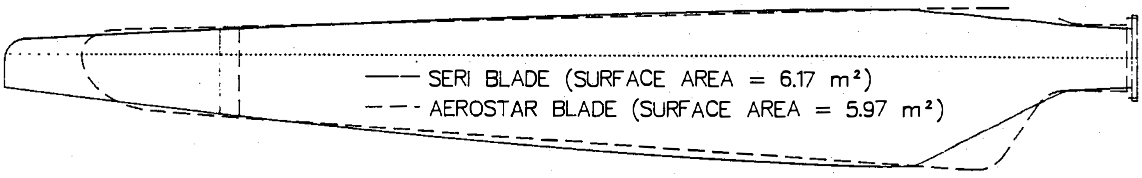

Figure 4. Overlay of SERI and AeroStar Blade

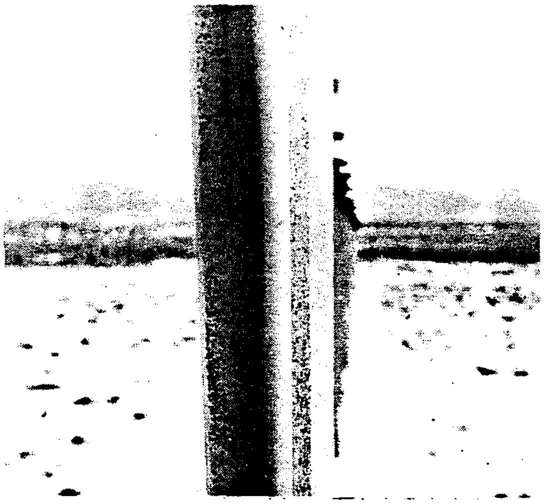

Figure 5. Simulated Leading-Edge Roughness

extended along the complete blade span and was placed with the strips' leading edge at 2% chord on the upper surface and at 5% chord on the lower surface. Grit height varied from 0.38 mm (0.015 in.) to 0.64 mm (0.025 in.), which is substantially larger than standard NACA roughness of 0.28 mm (0.011 in.). The grit distribution and density were considered representative of the effects of significant insect, oil, and dirt accumulation as discussed by Musial et al. (6).

For the performance comparison, both the data sampling rate and peak power limit had to be established for the machines. Based on the relative position of the anemometer tower and the test turbines, data were collected at 1 Hz and block averaged for 30 seconds to satisfy the AWEA performance standard (7). The peak power setting for the two turbines was based on the Micon 65/13 large generator rating of 65 kW. Most of these machines are operated above this power level at a blade pitch that results in a peak generator output in the range of 70 to 80 kW. Frequent generator overtemperatures and machine shutdowns will occur for 30 second block averaged peak power above this range.

3.1 Clean Blades

A comparison of generator power versus wind speed for clean blades is shown in Figure 6. For the SERI blades a peak power of 67 kW at 13.4 m/s (30 mph) was achieved by setting the 75% blade radius pitch at 4.2 deg toward feather with respect to the airfoil's chord line. For the AeroStar blade, a peak power of around 75 kW is achieved at 17.9 m/s (40 mph) using a 0.5 deg blade pitch at 75% radius with respect to the airfoil's chord line. This is the commonly used blade pitch for AeroStar blades in the San Gorgonio wind farms that keeps the peak power below the point where the overtemperature switch cuts the generator out. For both sets of blades, the peak power can be shifted up or down approximately 10% with a 1 deg blade pitch change toward feather or stall, respectively. Each power curve is bounded by a ±1 sigma band standard deviation. Up to 13.4 m/s (30 mph) the standard deviation is slightly less for the SERI blades. Above this speed it is somewhat greater for the SERI blades. Included in the standard deviation are infrequent power spikes which occur for both machines at wind speeds close to or just beyond their respective peak powers. These power spikes were seen to occur only a few times in 12 hours when the wind was between 13.4 m/s (30 mph) and 17.9 m/s (40 mph). The power spikes were in the 100 kW range and lasted a few seconds. For the SERI blades they tended to be somewhat greater in magnitude and shorter in duration than for the AeroStar blades. This difference is thought to be related to the difference in aerodynamic characteristics between the two rotors. Work is currently in progress to determine the significance of these power spikes.

The corresponding generator power coefficient (C_p) versus wind speed is shown in Figure 7. The nondimensional coefficient eliminates the difference in performance due to radius for the comparison between the blades, and it only discerns aerodynamic differences caused by blade geometry (i.e. planform, twist, and airfoils). Values of C_p at low wind speeds may be abnormally high because of the two-speed generator switching from 13 kW to 65 kW and vice-versa. Although the absolute magnitudes of the C_p at low wind speeds may be questionable, the relative difference between the two curves is considered accurate. Because of the SERI blades' greater aerodynamic efficiency, the rotor switches from the small to large generator at a lower wind speed than the AeroStar rotor and spends a greater percentage of time on the large generator.

The improvement of the SERI rotor between 4.5 m/s (10 mph) and 6.7 m/s (15 mph) drops below 5% at higher wind speeds and goes to zero at 12.1 m/s (27 mph). Above 12.1 m/s (27 mph) the aerodynamic efficiency of the SERI blades is designed to drop dramatically in order to control peak power. The 20% drop in C_p at 15.6 m/s (35 mph) is achieved through a similar drop in airfoil C_{lmax} over the tip region of the blade. Although the nondimensional aerodynamic efficiency of the SERI blades drops below the AeroStar blades at 12.1 m/s (27 mph), the additional swept area of the SERI blades delays the dimensional power from dropping below that of the AeroStar blade until 14.3 m/s (32 mph) as indicated in Figure 6.

3.2 Dirty Blades

A comparison of the generator power versus wind speed for dirty blades is shown in Figure 8. Over the whole wind speed range the SERI blades show a dramatic improvement in power output over the AeroStar blades. The improvement ranges from 30% at low wind speeds and peaks out at 37% at 10.3 m/s (23 mph) before dropping to 30% at 13.4 m/s (30 mph). The peak power of the SERI blades at 13.4 m/s (30 mph) drops from 67 kW for clean blades (Figure 6) to 60 kW for dirty blades, which results in a decrease of 10%. At the same wind speed the AeroStar power drops from 64 kW for clean blades (Figure 6) to 46 kW for dirty blades which results in a decrease of 28%. A similar comparison at 17.9 m/s (40 mph) shows the power output of the SERI blades dropping from 62 kW for clean blades to 56 kW for dirty blades for a 10% decrease. The power output of the AeroStar blades, on the other hand, drops from 75 kW for clean blades to 52 kW for dirty blades for a 31% decrease. For similar roughness effects this comparison clearly demonstrates the minimal roughness sensitivity of the SERI airfoils relative to the NACA 44XX series airfoils. The standard deviation for both the SERI and AeroStar dirty blades decreases relative to the clean blade case for wind speeds above 13.4 m/s (30 mph). However, the SERI blades still have a greater standard deviation than do the AeroStar blades at high wind speeds.

The corresponding generator C_p versus wind speed is shown in Figure 9. The dirty blade efficiency difference, which represents combined roughness and aerodynamic improvements, is in favor of the SERI blades for all wind speeds up to 16.1 m/s (36 mph). The large difference in efficiency at low wind speeds results in better starting characteristics for the SERI blades and earlier transition to the large generator. In the dirty blade state the AeroStar blades have a difficult time getting off the small generator and experience more on/off cycles. The improvement seen in Figure 9 for the SERI blades is in the 12% to 19% range for wind speeds of 4.9 m/s (11 mph) to 13.9 m/s (31 mph). With the efficiency improvement, resulting from less sensitivity to roughness effects, the point at which the aerodynamic efficiency of the SERI blades drops below that of the AeroStar blades shifts from 12.1 m/s (27 mph) for clean blades to 16.5 m/s (37 mph) for dirty blades.

3.3 Performance Improvements

The performance envelope for measured power output improvements of the SERI blades over the AeroStar blades is shown in Figure 10. The lower boundary of the envelope for clean blades is comprised of improvements due to swept area and aerodynamics. In addition to these two components, the upper boundary for rough blades includes the improvement resulting from the new airfoil's minimal sensitivity to roughness effects. This operating envelope indicates that the SERI blades will generally produce 20% to 30% more power at most wind speeds than will the AeroStar blades. The rapid rise in improvement for the low wind speed range 4.5 to 6.3 m/s (10 to 14 mph) is related to the improved startup characteristics of the SERI blades.

The envelope of power output improvements of the SERI blades over the AeroStar blades can be broken down into

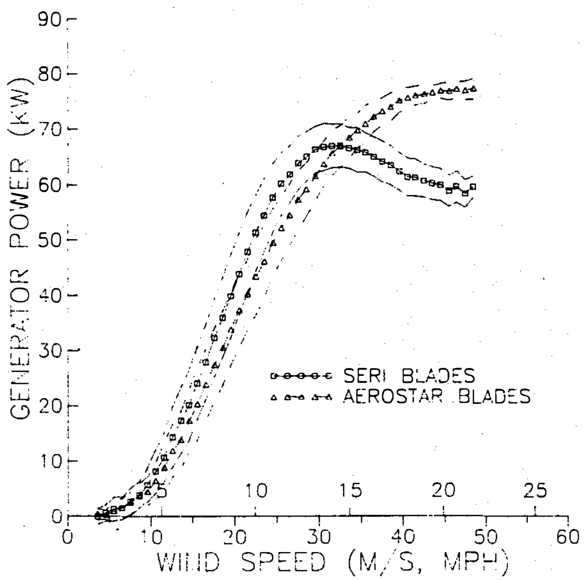

Figure 6. Clean Blade Generator Power

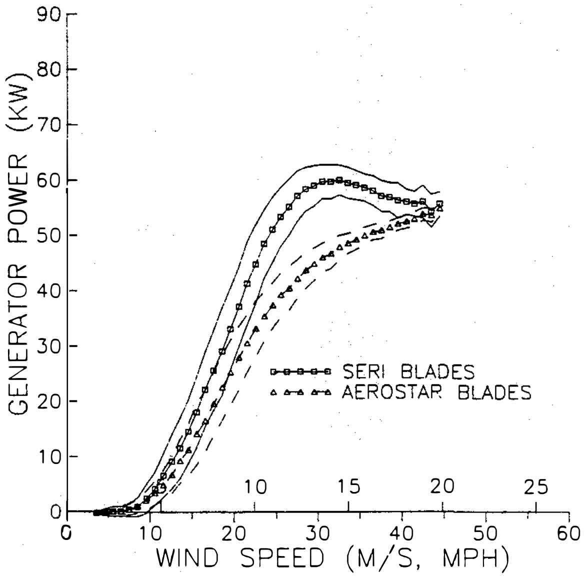

Figure 8. Dirty Blade Generator Power

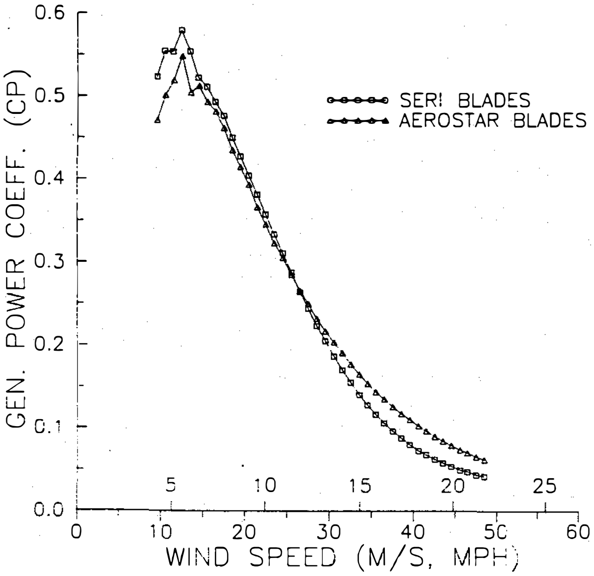

Figure 7. Clean Blade Power Coefficient

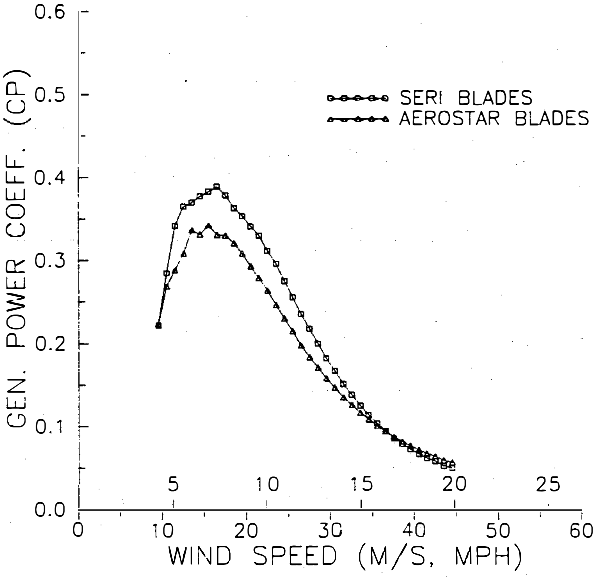

Figure 9. Dirty Blade Power Coefficient

three components (Figure 11). In order of their relative contributions, these components are:

1. Greater swept disc area
2. C_{lmax} roughness insensitivity
3. Aerodynamic improvements.

For a stall-regulated rotor the thin-airfoil family, which has a restrained C_{lmax} in the tip region, allows the use of 14% more swept disc area for a given generator rating. The thin-airfoil family has a C_{lmax} in the tip region about 25% lower than for conventional airfoils. This reduction in C_{lmax} allows a similar reduction in peak rotor power, which is proportional to C_{lmax} over the outboard region of the blade. Increased swept area benefits energy production for all wind speeds, whereas the other two power improvement components are wind speed dependent.

The second largest contributor to power improvement is related to the design feature of the airfoil family that makes its C_{lmax} relatively insensitive to blade surface roughness effects. Blade leading-edge roughness normally results from insect accumulation along with airborne pollutants of oil and dirt. The effects of roughness are wind speed dependent. At low wind speeds the roughness insensitivity of the airfoils results in better startup characteristics with more time on line. From 6.7 m/s (15 mph) on up, the improvement increases continuously before leveling out at over 20% around 13.4 m/s (30 mph). As the blade stalls from root to tip with increased wind speed, it exhibits improved tolerance to surface contamination. Because the SERI airfoil's C_{lmax} is less sensitive to roughness effects than conventional airfoils, the characteristic drop-off in peak power associated with such airfoils is avoided.

The thin-airfoil family is also designed to provide better aerodynamic performance characteristics in terms of C_l and C_d. At the blade root the maximum ratio of lift-to-drag is designed to occur at high values of C_l. The C_{lmax} of the airfoil family, which is greatest toward the root, decreases in a continuous manner toward the tip. This trend is considered desirable because it results in greater aerodynamic efficiency over the important energy-producing medium wind speed range.

The blade geometry, in terms of blade taper and twist, is chosen to complement the performance characteristics of the

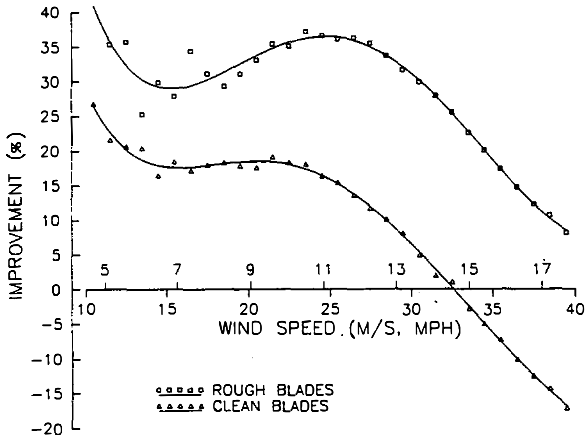

Figure 10. Generator Output Improvement
(SERI Blade/AeroStar Blade)

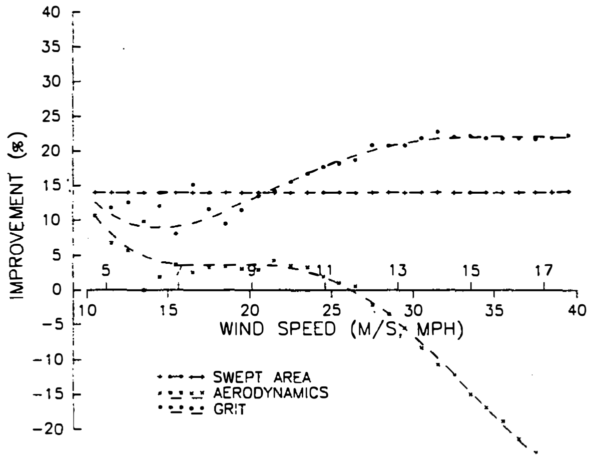

Figure 11. Generator Output Improvement Components
(SERI Blade/AeroStar Blade)

thin-airfoil family. A greater taper ratio than that employed on other stall-regulated blades enhances the power output at low to medium wind speeds. It also aids the tip region airfoil's control of peak power at high wind speeds. The combination of a large inboard blade chord and twist with more desirable blade root airfoil characteristics also leads to more run time at low wind speeds. The improved low wind aerodynamic efficiency drops to around 4% at 6.7 m/s (15 mph) and stays relatively constant until 10.7 m/s (24 mph). Then the aerodynamic efficiency is designed to rapidly decrease such that the blade is 20% less efficient than the AeroStar blade at 15.6 m/s (35 mph). This is achieved primarily with a low tip region C_{lmax} aided by slightly less tip chord. This rapid drop-off in aerodynamic efficiency at high wind speeds is necessary to neutralize the extra power produced from 14% more swept disc area.

Energy output improvements of the SERI blades over the AeroStar blades will be site dependent. Based on the power curves from this study and independent tests of the SERI blades at Calwind Resources Inc. and Energy Unlimited Inc., overall energy improvements of 15% to 30% can be expected for most wind sites. Desert sites with little or no blade soiling will likely be in the lower half of this range; while sites where insect accumulation is a problem can be expected to be in the upper half of this range.

4. CONCLUSIONS

The performance characteristics of airfoils designed for aircraft are largely incompatible with the needs of stall-regulated rotors. The SERI thin-airfoil family was designed to overcome these shortcomings for both existing and future wind turbines. Atmospheric test results of the thin-airfoil family on a geometrically optimized blade have demonstrated the following generator power output improvements relative to the AeroStar blade.

- Clean blade power improvement of 15% to 20%
- Dirty blade power improvement of 27% to 35%.

These improvements are attributed to increased swept area, greater airfoil C_{lmax} tolerance to roughness effects, and improved aerodynamics. Incremental improvements associated with each of these are listed in their respective order of importance.

- Swept rotor area: SERI airfoils allow for a 14% increase over current airfoils without a peak power problem resulting.
- Roughness tolerance: SERI airfoils improve dirty blade power output 10% to 20% above that of the NACA 44XX series airfoils.
- Aerodynamics: Power output improvements resulting from the combined effects of better airfoil lift-to-drag ratio along with blade taper and twist were 5% to 10% at low wind speeds and 3% to 4% at moderate wind speeds, with decreasing aerodynamic efficiency at high wind speeds to control peak power.

5. ACKNOWLEDGMENTS

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