NREL/CP-500-22082 • UC Category: 1211

CONF-970135--

The Effects of Variable Speed and Drive Train Component Efficiences on Wind Turbine Energy Capture

L.J. Fingersh
M.C. Robinson
National Wind Technology Center
National Renewable Energy Laboratory

Presented at
ASME/AIAA Wind Energy Symposium
Reno, NV
January 6–9, 1997

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Work performed under task number WE711330

May 1998

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling (423) 576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

THE EFFECTS OF VARIABLE SPEED AND DRIVE TRAIN COMPONENT EFFICIENCIES ON WIND TURBINE ENERGY CAPTURE

L. J. Fingersh, M. C. Robinson
National Renewable Energy Laboratory
National Wind Technology Center
Golden, Colorado

Abstract

A wind turbine rotor achieves optimal aerodynamic efficiency at a single tip-speed ratio (TSR). To maintain that optimal TSR and maximize energy capture in the stochastic wind environment, it is necessary to employ variable-speed operation. Conventional constant-speed wind turbines have, in the past, been converted into variable-speed turbines by attaching power electronics to the conventional induction generator and gearbox drive train. Such turbines have shown marginal, if any, improvement in energy capture over their constant-speed counterparts. These discrepancies have been shown to be the result of drive train components that are not optimized for variable-speed operation. Traditional drive trains and power electronic converters are designed to achieve maximum efficiency at full load and speed. However, the main energy producing winds operate the turbine at light load for long periods of time. Because of this, significant losses to efficiency occur. This investigation employs a quasi-static model to demonstrate the dramatic effect that component efficiency curves can have on overall annual energy capture.

Introduction

A fixed-pitch wind turbine achieves optimum aerodynamic rotor performance at a single tip-speed ratio (TSR). Using variable speed, this optimal TSR can be maintained throughout much of the turbine's operating envelope. Theoretically, 15% to 20% increases in energy capture can be achieved over conventional constant-speed designs with equivalent energy capture areas.[1] In order to take advantage of this enhanced performance, some constant-speed machines have been modified to operate in a variable-speed mode.[2] These turbines, however, have shown only marginal improvement in energy capture.

In order to understand this discrepancy, a static analysis of energy capture potential has been performed here. Three turbines were evaluated: (1) a conventional induction generator design operating at constant speed; (2) a conventional induction generator operating at variable speed using standard power electronics; and (3) a direct-drive, permanent-magnet machine operating at variable speed using standard power electronics. A standard Rayleigh wind distribution was used to evaluate the energy capture potential of each design. All machines were simulated using identical aerodynamic performance characteristics. When used in the constant-speed mode, these aerodynamic performance characteristics provided maximum energy capture efficiency at a site with Rayleigh average wind speed of 5.85 m/s. All results were normalized to the performance of the constant-speed turbine in order to permit a direct comparison of results.

The performance of these three "theoretical" turbines are representative of current turbine designs. The aerodynamic characteristics and component efficiencies used in the analysis were derived from actual component tests conducted at the National Wind Technology Center or from manufacturer's provided data and are representative of current applications. The integrated performance and potential energy capture reported here do not reflect the capabilities of any existing commercially available machine.

Obviously, numerous practical design trade-offs must be made when building turbines with such diverse operating paradigms. It is not the intent of the authors to discuss either the overall merits or detriments of these designs, but rather, to compare the energy capture performance potential when conventional constant-speed designs are converted to variable-speed operation using typical "industry standard" components. This paper focuses primarily on the potential aerodynamic gains from variable-speed operation and the degradation of these benefits through drive train and power electronics efficiency losses when industry standard components are used in non-optimal applications.

Nomenclature

w = *current windspeed*
$\bar{w}$ = *average windspeed*

$\rho = air\ density$

$A = rotor\ swept\ area$

$C_p = rotor\ power\ coefficient$

$$TSR = \frac{blade\ tip\ speed}{windspeed}$$

$\omega = rotor\ rotation\ rate\ (rad\ /\ s)$

$$Rayleigh = \frac{\pi w}{2\bar{w}^2} e^{-\pi\left(\frac{w}{2\bar{w}}\right)^2}$$

$$Available\ Energy = \frac{1}{2}\rho A w^3 \cdot (Rayleigh\ \% \cdot 8760)$$

$$Mechanical\ Energy = C_p \cdot Available\ Energy$$

$$Mechanical\ Power = \frac{1}{2}\rho A w^3 C_p$$

$$RPM = \frac{TSR \cdot w}{Radius} \cdot \frac{30}{\pi}$$

$$Power\ Out = Power\ In \cdot Component\ Efficiency$$

Discussion

The Rayleigh wind distribution used for this analysis and the resulting annual energy are shown in Figure 1. The energy capture potential for the three turbine configurations was obtained by a simple integration of the available energy distribution corrected at each wind speed for aerodynamic, gearbox, and generator efficiency losses.

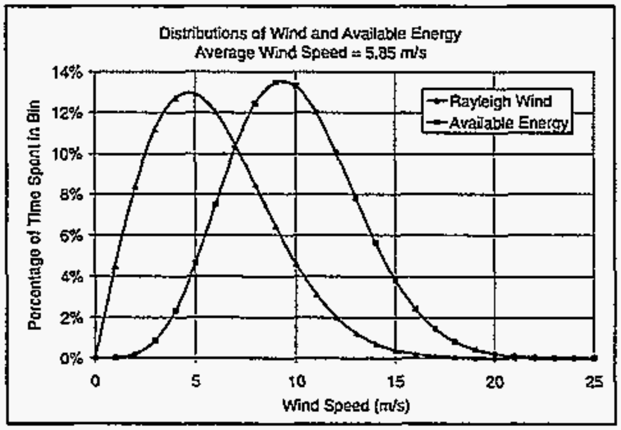

Figure 1 - Distribution of available wind and available energy in a Rayleigh wind regime

Aerodynamic Efficiency

The aerodynamic efficiency presented as a plot of C_p vs. wind speed for variable-speed and constant-speed operations is shown in Figure 2. From this figure, the relative merit of variable speed operation can readily be observed. Although constant-speed operation enables a higher peak C_p in a narrow range, variable-speed operation allows operation at a higher C_p at lower wind speeds because the optimum rotor tip-speed ratio can be maintained. Also, near rated power, a constant-speed rotor begins to stall and therefore loses efficiency. A variable-speed turbine can be controlled more accurately near stall and can therefore maintain a higher power coefficient near rated power. This accounts for the higher power coefficient of the variable-speed turbine from 10 to 17 m/s in Figure 2.

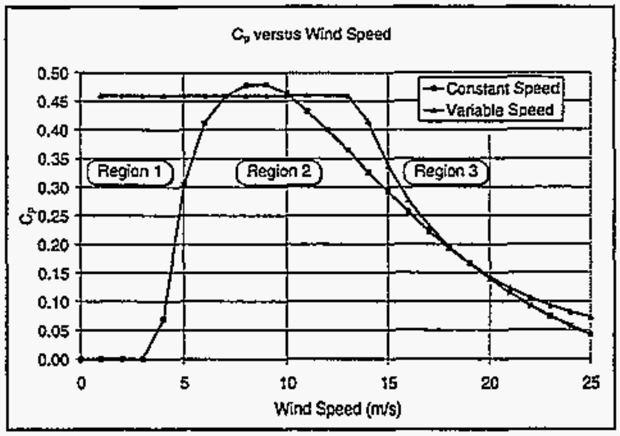

Figure 2 - C_p vs. windspeed for a rotor operated constant speed and variable speed

By convention, the turbine operating envelope is broken into three regions. Region 1 defines the turbine cut-in speed where sufficient aerodynamic power is produced to initiate energy collection. Region 2 is defined as the operating regime between turbine cut-in and maximum power. In this region it is desired to maximize energy capture. Region 3 is the region in which the turbine operates at or above maximum power. In this region power must be limited in order to prevent damage to the turbine.

In general, variable-speed operation permits an earlier cut-in speed (4 or 5 m/s vs. 6 m/s respectively for the variable-speed and constant-speed machines examined here) which enhances energy capture for variable-speed at low wind speeds. This difference reflects the simple aerodynamic constraints placed on the two designs. For variable-speed operation, the aerodynamic efficiency remains optimized by holding TSR at the design constant. This achieves an optimized blade angle-of-attack for maximum aerodynamic torque independent of wind speed. Thus, even at very low wind speeds, net positive mechanical power is always produced.

A constant-speed machine is also optimized for a single TSR. This TSR usually corresponds to the wind speed at which the greatest amount of energy is available (≈ 8.5 m/s in Figure 2). Since this machine is constrained to a single RPM, optimal efficiency can be achieved only at this single wind speed. The shape of C_p curve directly reflects the aerodynamic efficiency loss when operating above or below this optimized design point.

In high winds, stall-controlled turbines depend on this loss to mitigate peak power by increasing the relative blade angle beyond stall. However, in low winds, the angle-of-attack decreases toward zero. In fact, some turbines have slightly negative pitch angles near the rotor tip. Depending upon the design constraints, negative mechanical power (motoring) is produced at low wind speeds. The windspeed sufficient to produce positive power determines the cut-in speed for constant-speed machines.

These same aerodynamic constraints highlight the performance increase in region 2 achieved with variable speed. Throughout this region (from cut-in to approximately 13 m/s), the variable-speed turbine maintains a constant tip-speed-ratio reflected as a constant C_p of 0.46 in Figure 2. The constant-speed machine's C_p varies, achieving a maximum (0.48) at the wind speed (≈ 8.5 m/s) for maximum energy density. It is the difference between these two curves which defines the net energy gain or loss from the aerodynamic efficiencies.

These differences are even more pronounced when the actual mechanical power is plotted as a function of wind speed (Figure 3). The direct-drive permanent-magnet machine performs the best because it has the lowest cut-in speed. Losses from the gear box (discussed later) in the variable-speed, induction-gear machine slightly increase its cut-in speed. Otherwise, this variable-speed machine tracks the energy capture capability of the direct-drive machine. The constant-speed machine performs only slightly better than the variable-speed machine around the optimal design point of 8.5 m/s due to the higher value of C_p. The net difference in energy capture potential between these machines will be discussed later.

For a purely static comparison of performance, the maximum C_p for variable speed should be equal to that of constant speed. The 4% reduction in peak value used in this quasi-static analysis reflects the inability of a variable-speed machine to truly track optimum TSR due to rotor inertia. Preliminary results from NWTC's variable-speed experiment[3] collected by one of these authors has shown this 4% reduction to be reasonable and, perhaps, conservative.

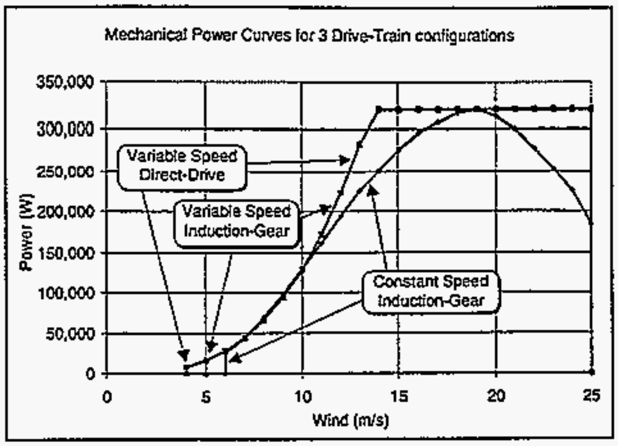

Figure 3 - Shaft power curves for constant-speed and variable-speed turbines

Generator Efficiency

Turbine designers spend a great deal of time optimizing the aerodynamic efficiency of the rotor to maximize energy capture. The proper selection and match of the generator and drive train efficiency is just as important in determining energy capture performance. When altering a conventional constant-speed machine to function in a variable-speed mode, a proper component integration is critical.

For purposes of this analysis, the overall efficiencies of a combined induction generator and gear box are compared with a direct-drive permanent magnet machine. A typical (measured) induction generator electrical conversion efficiency as a function of input mechanical power is shown in Figure 4. Inherently, all electrical devices must be efficient at maximum power for heat dissipation considerations and 97% to 98% efficiencies are not unreasonable. However, the efficiencies at lighter loads are often much lower (as shown in Figure 4). The degree to which the overall energy capture capability is degraded by this poor low-end performance depends primarily upon the relative contribution of energy collected at lower power levels to the overall energy total.

The same design premise is true for gear boxes as well. Maximum efficiency is achieved at maximum power and drops off rapidly at the low end. When operating a conventional gear box at variable speed, conversion efficiency is a function of both rated mechanical power and RPM. An example of measured gearbox performance is shown in Figure 5 where the conversion efficiency is represented as a surface. In industrial applications, induction motor and gear box combinations are not often utilized in a variable-speed mode and this type of efficiency data can be very difficult to obtain.

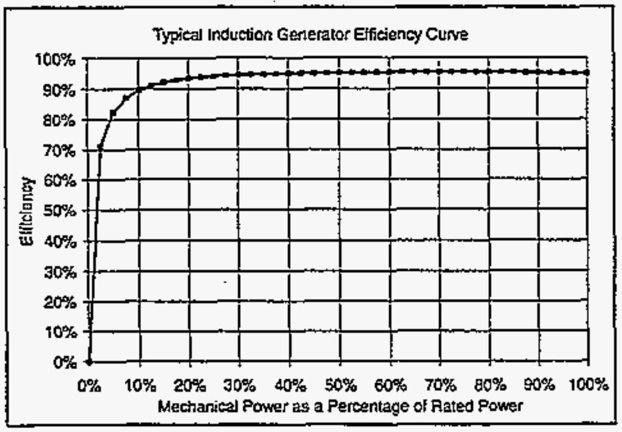

Figure 4 - Generator efficiency curve for a typical high-efficiency induction generator in the 275kW class

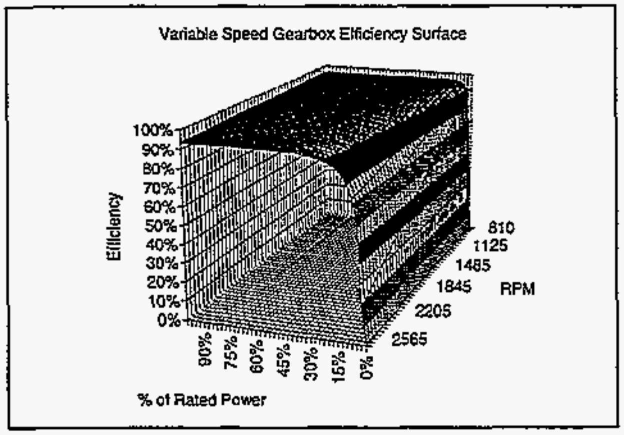

Figure 5 - Typical efficiency surface for a wind turbine gear box

In contrast, a typical permanent-magnet generator efficiency is high at low power ratings and decreases slightly with increasing power. This efficiency is also RPM dependent. An example is shown in Figure 6 where a complex two parameter surface shows efficiency at any operating point. In general, the higher efficiency at lower wind speeds (lower power rating) combined with direct drive (no gear box losses) offers a substantial improvement in potential energy capture when compared to induction motor designs.

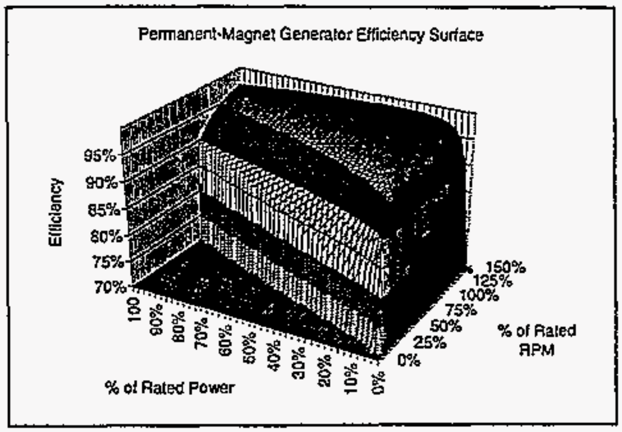

Figure 6 - Efficiency surface for a direct-drive, permanent-magnet generator

Power Electronic Efficiency

Variable-speed turbines must have power-electronic converters to convert the variable-frequency output of the generator to the constant frequency of the power grid. Since some or all of the power of the turbine must pass through the converter, the efficiencies of the converters can also have a drastic impact on electrical energy capture. A curve of efficiency versus percent of rated load for a typical power-electronic converter is plotted in Figure 7. Again, very high efficiencies are achieved at the maximum power rating while significant losses occur at lower power ratings. For comparison purposes, two theoretical converters with flat efficiencies of 90% and 94% are also included. Although not currently available, converters with these characteristics are theoretically possible using variable switching frequency and/or multiple small converters utilized in succession. Converters with constant efficiencies over the range from 0.1% to 100% of rated power have been demonstrated at low power levels.

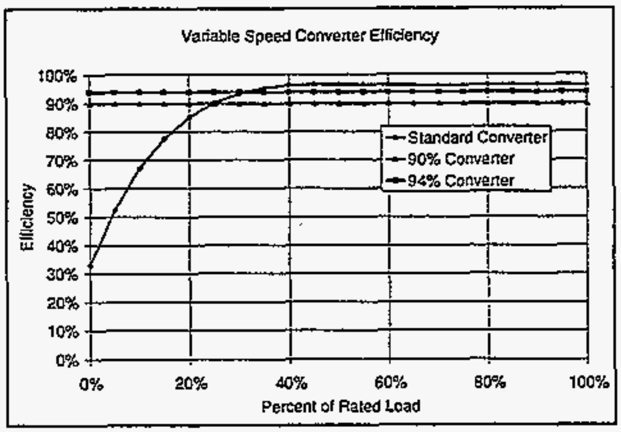

Figure 7 - Efficiency curves for power-electronic converters.

Table 1. Energy Capture Potential
Percentage of 5.85 m/s Rayleigh-Betz Energy

Design Config.	Energy Converted to Electricity	Aerodynamic Losses Below Rated	Aerodynamic Losses Above Rated	Generator Losses	Gearbox Losses	Converter Loses	Losses while not operating below cut-in and above cut-out
IG-CS	57%	27%*	-	4%	5%	0%	7%
IG-VS-STN	55%	19%	6%	4%	5%	8%	3%
IG-VS-90%	57%	19%	6%	4%	5%	6%	3%
IG-VS-94%	59%	19%	6%	4%	4%	4%	3%
PM-VS-STN	63%	19%	6%	2%	0%	9%	1%
PM-VS-90%	65%	19%	6%	2%	0%	7%	1%
PM-VS-94%	68%	19%	6%	2%	0%	4%	1%

*** The point at which a stall-regulated constant-speed turbine begins to power regulate is not well defined. Therefore, this number is the combined aerodynamic losses both below and above rated power.**

Results

The overall energy capture potential for a conventional induction generator operating at constant speed ("IG-CS"), an induction generator operating at variable speed ("IG-VS") and permanent magnet machine operating at variable speed ("PM-VS") is presented in Table 1. Variable-speed operation is further refined assuming a standard power converter ("-STN") and a 90 and 94% efficient converter respectively ("-90%" and "-94%"). The energy capture potential for the three turbine configurations was obtained by a simple integration of the available energy distribution corrected for aerodynamic, gear box and generator efficiency losses. Note that the percentages given in the table are percentages of the total energy that would be captured by a machine operating at Betz limit (16/27 efficiency) at all times in a 5.85m/s Rayleigh wind distribution.

The most startling result from this simple quasi-static analysis is the decrease in energy capture potential of a conventional constant speed machine converted to variable-speed operation. The net improvement from variable-speed aerodynamics (operating at optimum C_p is very small (only 2%) over the constant-speed machine. A larger improvement (4%) is obtained from the improved cut-in wind speed performance. As noted earlier, this overall 6% gain is more than eliminated by the 8% decrease from standard converter loses. The net operating efficiency of the variable-speed machine is actually 2% less than the standard constant-speed machine. Although performance improves when the theoretical 90% and 94% converters are used (+2% and +4% respectively), these values are probably not large enough to justify the added costs associated with variable-speed power-electronic components.

The net operating energy capture efficiency improves by 6% compared to constant speed when a direct-drive, permanent-magnet generator is used in the variable-speed turbine. Again, improved aerodynamics accounts for only 2% of this increase. Improvements in cut-in speed (6%), generator loss (2%) and gearbox loss (5%) also contribute. Even though the net loss from the standard energy converter (9%) diminishes these improvements, an overall 6% increase in conversion efficiency (and therefore approximately 10% improvement in energy capture) is very attractive. Further improvements could be realized if the theoretical converters were used.

This simple analysis can easily be extended to other wind distributions. Using the same turbine designs (optimized for a 5.85 m/s mean), the effects of variations in the average Rayleigh distribution can be contrasted. Figure 8 shows the overall energy capture efficiency (conversion of wind into electricity) for all seven turbine configurations as a function of Normalized Rayleigh Average Wind Speed. Figure 9 indicates the net improvement/loss in energy capture performance over a constant-speed machine across Rayleigh distributions. A normalized wind speed of 1.0 corresponds to a 5.85 m/s Rayleigh average wind speed and represents the performance values reported in Table 1.

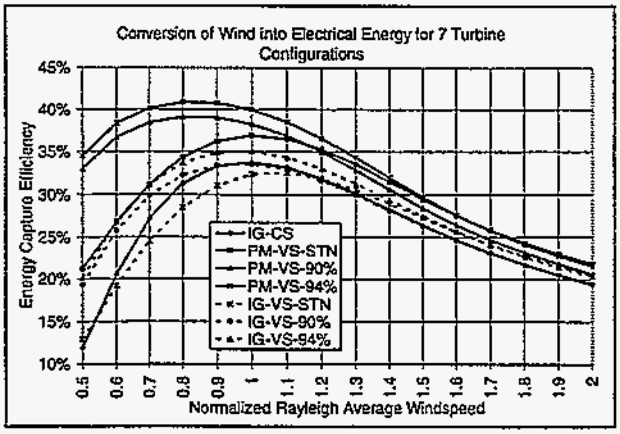

Figure 8 - Efficiency of converting wind into electricity for several drive train configurations. See text for explanation of labels. Note that the constant speed turbine is optimal at 1.0. The variable-speed turbines use the same aerodynamics but are optimal elsewhere. If one compares efficiencies at optimal Rayleigh wind speeds for each turbine instead of those points at 1.0, variable speed would look slightly better.

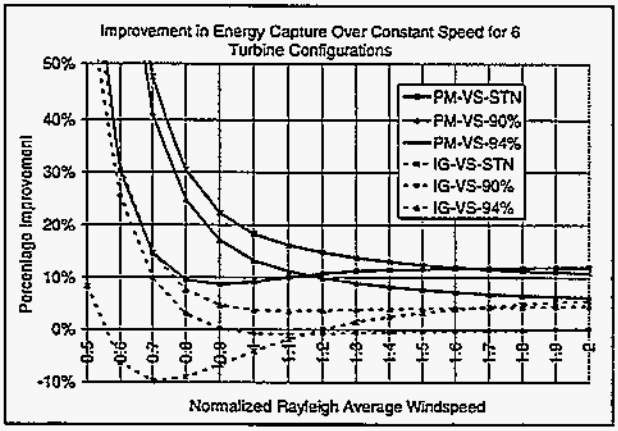

Figure 9 - Improvement or reduction in energy capture versus a constant-speed turbine

These figures provide some insight into the off-optimal design performance. As one would expect, the overall energy capture efficiency diminishes with increasing mean wind speed. More energy is available at the optimal design C_p and the wind energy available at wind speeds which exceed the machine maximum power limit will be lost. Similarly, improvements over constant-speed operation (Figure 9) rapidly converge asymptotically, ultimately reflecting the differences in the power-electronic conversion efficiencies.

Performance metrics at lower wind speeds are much more interesting. Significant improvements are made with variable-speed architectures and permanent-magnet generators over an equivalent constant-speed machine design. These improvements can be as high as 30% when the average Rayleigh wind speed is 80% of the constant speed design optimum and non-standard "flat response" converters are used. Even a constant-speed machine converted to variable speed, with all of the inherent component loses, shows better performance as long as the non-standard converters are used. Using the standard converter, overall performance continues to deteriorate at low wind speeds, attaining energy capture potentials 10% to 15% worse than the constant speed machine.

Conclusion

Maximum wind energy capture for fixed-pitch rotor systems can only be achieved through variable-speed operation. Variable-speed implementation costs and the corresponding potential net performance gains have been a topic of debate for some time. Often, negligible performance improvements from constant-speed machines which have been converted to variable-speed operation are cited as one of the reasons not to pursue this technology.

This analysis suggests that simple applications of existing industry standard technology to achieve variable-speed operation will not produce the desired energy capture enhancements. Limitations on individual component efficiencies, especially the current power electronic conversion capabilities, preclude simple retrofits of existing constant-speed turbine designs. Only by utilizing advanced direct-drive architectures and continuing to invest in more advanced power electronic conversion capabilities can the full benefits of variable-speed operation be realized.

Ultimately, the decision to implement these advanced architectures will be made only after a significant investment has been made in rigorous and comprehensive design trade-off studies. Such investigations must include not only financial considerations but an understanding of the dynamic effects on structural fatigue life arising from variable-speed operation.

Acknowledgments

The U. S. Department of Energy is credited for its funding of this document through the National Renewable Energy Laboratory under contract number DE-AC36-83CH10093.

References

[1] Carlin, P. "Some Analytic Expressions for Upper Limits on the Mean Annual Wind Turbine Power in a Rayleigh Wind Regime." *Proceedings of the Wind Energy Symposium*, January 1997, Reno, NV. Reston, VA: American Institute for Aeronautics and Astronautics.

[2] Milborrow, D. "Are Variable Speed Production Benefits Being Oversold?" *WindStats Newsletter*, Spring 1996, Vol. 9, No. 2, pp 6-7.

[3] Carlin, P. Fingersh, L. "Some Preliminary Results from the NWTC Direct-Drive, Variable-Speed Test Bed." *Proceedings of the Wind Energy Symposium*, January 1997, Reno, NV. Reston, VA: American Institute for Aeronautics and Astronautics.