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Assessing the Potential of a Mechanical Continuously Variable Transmission for Wind Turbines

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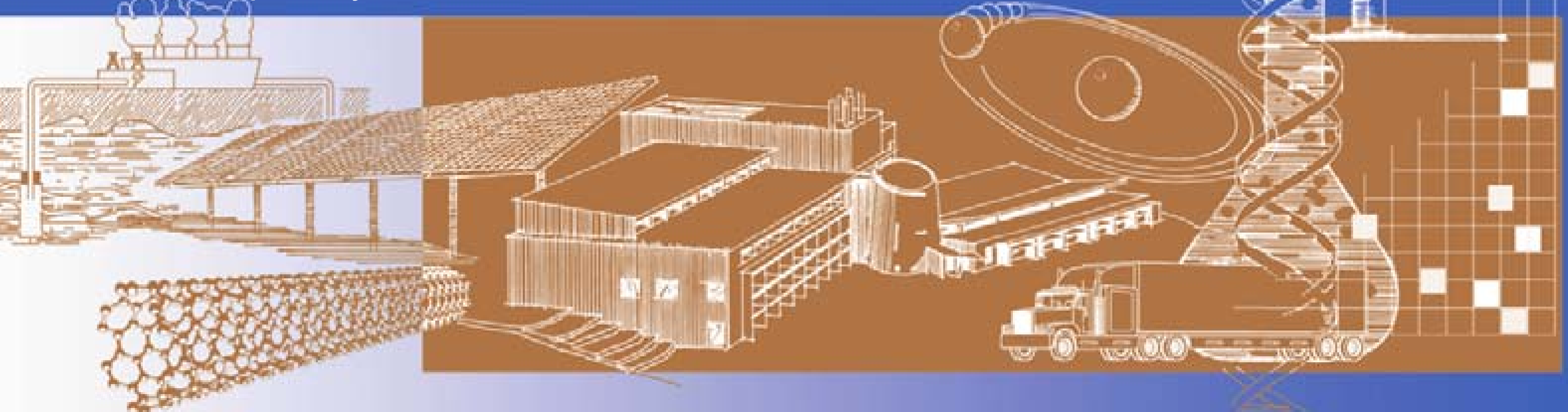

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Introduction

This paper provides an update to a previous report (1) that summarizes the results of a cooperative research and development agreement (CRADA) between the National Renewable Energy Laboratory (NREL) and Fallbrook Technologies, Inc. (Fallbrook).

The purpose of the CRADA is to assess the usefulness of a continuously variable transmission (CVT) for wind turbine applications. The NuVinci ™ CVT is a new type of rolling traction transmission that uses balls to vary the transmission ratio. The CVT is capable of rapid ratio changes and torque spike absorption and may be directly applicable to variable-speed wind turbine designs. This approach potentially offers a less expensive mechanical alternative to the use of power electronics (PE) currently used in large and small machines for variable-speed operation.

NREL examined the CVT technology for potential economic and performance benefits when integrated into conventional wind turbine designs. The WindPACT 1.5-MW wind turbine was used as a baseline design (2). NREL determined the cost of energy (COE) differences from the baseline by replacing the WindPACT drive train with a CVT drive train scaled to 1.5 MW. NREL used CVT efficiency curves and capital cost estimates furnished by Fallbrook to perform the analysis.

Figure 1 is an exploded view of a Fallbrook Technologies CVT variator. The variator is the transmission component that allows smooth, continuous transition between an infinite number of gear ratios. The variator transfers power between an input disc and an output disc. The balls transmit power from the input disc to the output disc using elastohydrodynamic lubrication. The transmission ratio is changed by varying the angle of the balls' rotational axes. The angle shown in the configuration in Figure 1 is changed by moving the idler along the longitudinal axis of the CVT. The Fallbrook CVT uses 3 to 20 balls, depending on the torque capacity desired. For a given diameter of the Fallbrook CVT, a greater number of balls provides a greater torque capacity. This scaling characteristic is commonly employed with conventional planetary gears, but it is unique to the Fallbrook CVT.

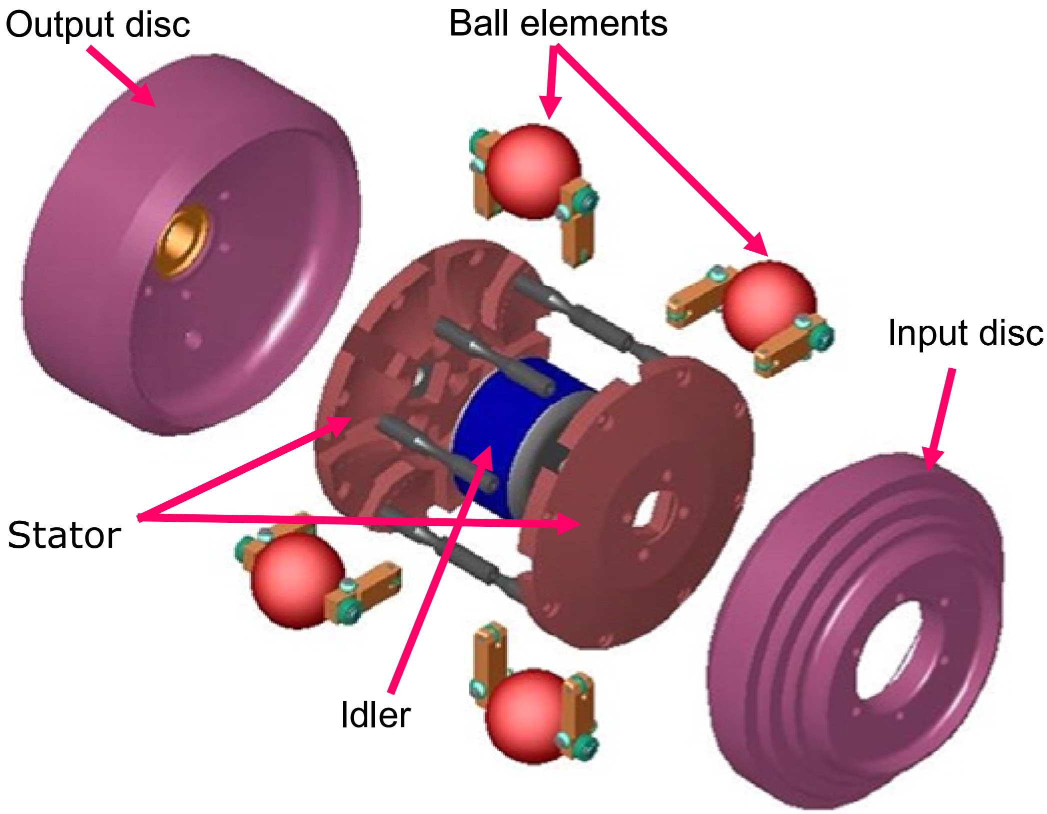

Figure 1. Exploded view of Fallbrook CVT variator with core components

There are several advantages of using CVTs on wind turbines. One is the possibility of a wider range of variable speed than the conventional doubly fed solution. For example, in the baseline turbine of the WindPACT Advanced Drive Train study, the cut-in (startup) wind speed is 3.0 m/s (~7mph). The wind turbine rotor speed remains at 12.3 rpm until the wind speed reaches 6.5 m/s. Then the rpm increases linearly with wind speed until the machine reaches rated power at 19 rpm (Figure 2).

This study assumes that the turbine configurations which use a CVT begin variable-speed operation at 5.0 m/s rather than 6.5 m/s. Starting variable speed operation at this lower speed yields approximately 0.6% (32 MWh per year) additional energy production.

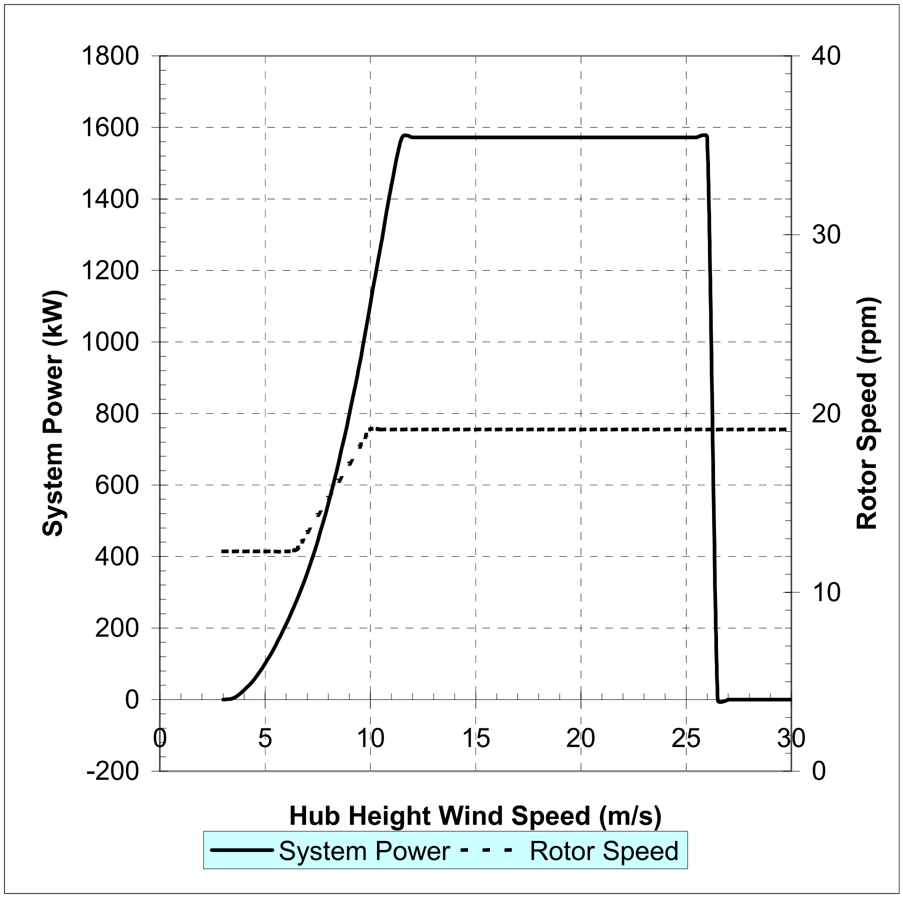

Figure 2. WindPACT power curve and rpm curve for a 1.5-MW turbine

A second advantage of a CVT is its potential to obtain variable speed with reliable and efficient permanent magnet (PM) generators or squirrel cage induction generators without maintenance-prone slip rings or expensive and relatively inefficient PE. A third advantage is that it is unlikely to infringe on the Kenetech patent on variable-speed systems (3), which is now owned by GE Wind Energy.

Cost of Energy Analyses

The COE for the CVT configurations was compared to results from the WindPACT Advanced Wind Turbine Drive Train Design Study. This study modifies the integrated mainframe baseline design used in the WindPACT study by replacing the third gearbox stage with a mechanical CVT capable of a 3.5 speed increase. All calculations performed in this study assume a 1.5-MW wind turbine, which is the size most commonly installed at onshore locations.

The Fallbrook CVT is still an emerging technology and has not yet been built in the sizes required to handle the large-torque loads generated by utility-scale wind turbines. Several assumptions were made regarding the costs of replacement, operations and maintenance, assembly, and testing. Generally, these costs were assumed to be equal to or slightly greater than those of the baseline turbines.

For the configuration in which the CVT is used with a two stage gearbox, the CVT was estimated by Fallbrook to cost $17,473. However, because the CVT was assumed to replace the third stage of the gearbox, the cost of the geared stages was assumed to be reduced by $10,000 to $110,000. For the configuration where the CVT was used with a single-stage gearbox, the CVT was estimated to cost $21,600 because of the higher torque levels applied to the CVT. The gearbox cost for this configuration ($90,000) was obtained from the WindPACT report.

The formula for the COE is calculated as

COE = (FCR*Capital Cost + Replacement Cost) / (Annual Energy Capture) + O&M costs

Fixed charge rate (FCR) is used to distribute the capital cost and financing details over a period of time. The annual energy capture is estimated by convolving the wind turbine power curve with an assumed wind speed distribution, such as the curve in Figure 2.

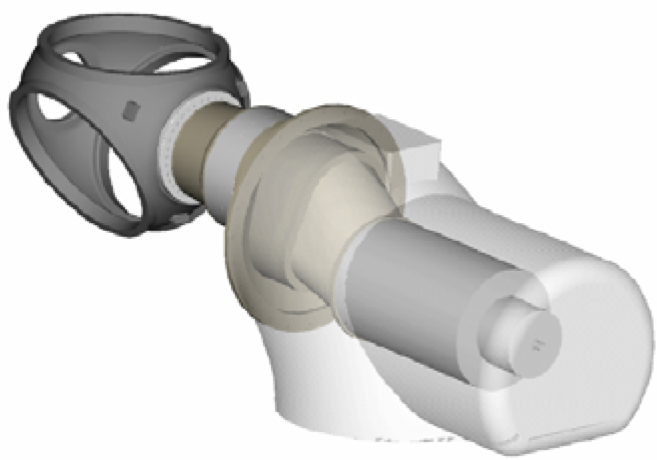

Figure 3. WindPACT integrated baseline

CVT Configurations

Two generators—the squirrel cage induction generator and the synchronous PM generator—were considered for use with the CVT. The advantages of the induction generator relative to the PM generator are:

- It has a lower capital cost.
- The slip provides some load absorption.
- It is widely available.

The advantages of a PM generator are:

- It is slightly more efficient.
- Its slow speed (many pole) designs permit the use of fewer geared stages.
- Does not consume reactive power.

In the WindPACT baseline, the three-stage gearbox has a ratio of 72:1 and is used with a 6-pole generator (1200 rpm). In this study, the CVT is assumed to replace the third stage of a three-stage gearbox when used with the induction generator. The gearbox has a first planetary stage followed by two parallel stages as assumed in the WindPACT drive train study.

The CRADA considered four CVT configurations. The previous report (1) examined CVT in standard operation, locked operation, and fixed carrier output. Since that time, a new proprietary configuration was identified as the most promising configuration due to the extended life and larger speed increase. The efficiency curve of this configuration is estimated to be the same as in the standard operating mode as presented in (1). The CVT efficiency used for all calculations in this paper are interpolated from the data provided by Fallbrook Technologies in Table 1.

Table 1. CVT Efficiency Data from Fallbrook Technologies Inc.

Slip Ratio	CVT Efficiency Data
0.44	84.2%
0.66	92.4%
0.71	94.0%
0.83	94.7%
0.93	95.4%
1	95.0%
1.14	95.5%
1.36	94.8%
1.57	93.8%
1.79	93.3%

Permanent magnet synchronous generators have the advantages of being slightly more efficient (less than 2%) than an induction generator and able to operate efficiently at low speeds. However, because synchronous generators have no slip, they must be decoupled from the grid to prevent dynamic loads from damaging the drive train. It may be possible to achieve this decoupling by actively controlling the CVT to increase the rotor speed during gusts. The energy in the gusts would be stored in the inertia of the rotor. The extent of the load mitigation for this control method would depend on the control limitations of the CVT. As a rough estimate, a synchronous generator would have to be controlled with bandwidth on the order of 60 Hz with a range of approximately 5%. In contrast, because of slip, an induction machine could withstand slower controls (approximately 3 Hz).

Several additional concerns regarding the controller exist. One concern pertains to the precision required by the CVT controller. The effects on energy capture and drive train life need to be explored as functions of controller precision.

Another concern is durability. Turbines are typically designed to run approximately 175,000 hours (nearly 20 years of continuous operation). Fatigue of the input and output discs is expected to be the primary concern. Other concerns relate to fatigue of the variator, the shift mechanism, and power rollers.

The COE results for two PM-CVT configurations are presented in Table 2. The single-stage gearbox with the PM generator leads to the lowest COE but has the highest risk due to the difficulty in gaining quick control of the drive train.

Table 2. CVT Results with an Integrated Mainframe

	WindPACT 1.5MW Integrated Baseline Turbine (3 stage gearbox)	Squirrelcage gen, 3.5X speed increase CVT, 2 Stage Gearbox	PM generator, 3.5X speed increase CVT, 2 Stage Gearbox	PM generator, 3.5X speed increase CVT, 1 Stage Gearbox
Drive Train & Nacelle				
Gearbox	$ 120,000	$ 110,000	$ 110,000	$ 90,000
CVT	$ -	$ 17,473	$ 17,473	$ 21,600
Support Structure	$ 21,000	$ 21,000	$ 20,000	$ 20,000
External Cooling System	$ 3,000	$ 3,000	$ 4,400	$ 4,400
Brake	$ 1,300	$ 1,300	$ 3,200	$ 3,200
Coupling	$ 2,100	$ 2,100	$ 2,400	$ 1,400
Nacelle Cover	$ 9,000	$ 9,000	$ 8,200	$ 8,200
Generator	$ 60,000	$ 42,000	$ 40,000	$ 47,000
Pow er conversion / conditioning	$ 61,800	$ 17,000	$ 7,000	$ 7,000
Substation VAR control	NA	$ 12,000	$ 12,000	$ 12,000
Transformer	$ 23,000	$ 23,000	$ 26,000	$ 26,000
Cable	$ 18,000	$ 18,000	$ 16,000	$ 16,000
Sw itchgear	$ 12,000	$ 12,000	$ 10,000	$ 10,000
Other subsystems	$ 25,000	$ 25,000	$ 25,000	$ 25,000
Drive train assembly and test	$ 4,900	$ 8,000	$ 8,000	$ 8,000
Turbine				
Rotor	$ 248,000	$ 248,000	$ 248,000	$ 248,000
Yaw Drive & Bearing	$ 16,000	$ 16,000	$ 16,000	$ 16,000
Control, Safety System	$ 7,000	$ 7,000	$ 7,000	$ 7,000
Tow er	$ 184,000	$ 184,000	$ 184,000	$ 184,000
Turbine Manufacture's Overhead & Profit (30%, tow er,rotor,and transformer excepted)	$ 108,330	$ 96,262	$ 92,002	$ 89,040
Balance of station	$ 358,001	$ 358,000	$ 358,000	$ 358,000
Figures of Merit				
Total Turbine	$ 1,282,431	$ 1,230,135	$ 1,214,675	$ 1,201,840
Drive Train component cost total	$ 361,100	$ 320,873	$ 309,673	$ 299,800
Percenatge of baseline drive train	100%	76%	74%	71%
Annual net energy production (kWh)	5,590,000	5,533,361	5,575,394	5,658,603
Percentage of baseline AEP	100%	99%	100%	101%
Replacement costs--LRC ($/yr)	5,100	5,100	5,100	5,100
O&M ($/yr)	24,596	24,347	24,532	24,898
O&M ($/kWh)	0.0044	0.0044	0.0044	0.0044
COE ($/kWh) = O&M+((FCR*ICC+LRC)/AEP)	$ 0.0296	$ 0.0289	$ 0.0284	$ 0.0278
Reduction in COE Compared to Integrated Baseline	**0.0%**	**2.5%**	**4.1%**	**6.1%**

Conclusions

Permanent magnet and squirrel cage induction generators were considered for use with a new Fallbrook CVT configuration. Given the assumptions of this study, the technology can lead to a COE reduction of between 3.7% and 7.3% for a conventional variable-speed drive train.

The CVT configurations result in lower capital costs than the machines used in the WindPACT study, partly because the CVT configurations use less PE and can operate at higher drive train efficiencies. The ability of the CVT to broaden the range of variable-speed operation increases the amount of energy produced on the order of 0.6% (approximately 32 MWh) and is reflected in the COE results in this report.

Future Work

The CRADA between NREL and Fallbrook Technologies was a preliminary investigation on the feasibility of using CVT technology on wind turbines. Further analytical work is needed to fully assess the COE reductions for wind turbines enabled by this CVT technology. For example, wind turbine simulations are needed to assess the CVTs effect on loads. The behavior of the drive train will affect how the turbine responds to wind gusts and the load spectrum applied to the machine. In addition, the use of the CVT to absorb torque spikes in the drive train requires further study. CVTs may also enable the use of larger generators for a given rotor size (higher specific power ratings) thereby increasing the amount of wind energy captured per turbine. The cost of increasing the size of the CVT to accommodate a larger generator is expected to be less than the cost of increasing the PE in a conventional system. Further study is required to determine the COE reductions possible by increasing the specific power ratings.

Although NREL is not presently researching CVT technology, Fallbrook is continuing to develop the NuVinci ™ CVT and has signed several agreements for bicycles, light electric vehicles, tractors, ATVs, and automobiles. In addition, several opportunities have been identified for using wind energy to power water irrigation, pumping, and purification. Agricultural irrigation and municipal water pumping use large amounts of energy that could be provided by wind turbines. In addition, recent attention has been given to the application of wind energy for purification technologies such as reverse osmosis. CVTs may enable the direct coupling of wind turbines to mechanically driven pumps for these applications. This coupling would reduce the capital cost of the turbine by avoiding the cost of power electronics and result in a higher overall efficiency by eliminating unnecessary electrical conversions.

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