Arnold Schwarzenegger
*Governor*

# DISTRIBUTED GENERATION DRIVETRAIN FOR WINDPOWER APPLICATION

INDEPENDENT ASSESSMENT AND FINAL EISG REPORT

*Prepared For:*
**California Energy Commission**
Public Interest Energy Research Program

*Prepared By:*
**Dehlsen Associates, LLC**

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# ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

## INDEPENDENT ASSESSMENT REPORT (IAR)

### DISTRIBUTED GENERATION DRIVETRAIN FOR WINDPOWER APPLICATION

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PIER Program Area: Renewable Energy Technologies

# PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace. The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which 5% is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Foundation through the California State University, which is under contract to the Commission.

The EISG Program conducts up to four solicitations a year and awards grants for promising proof-of-concept energy research.

PIER funding efforts are focused on the following seven RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Energy Innovations Small Grant Program
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally-Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The EISG Program Administrator is required by contract to generate and deliver to the Commission an Independent Assessment Report (IAR) on all completed grant projects. The purpose of the IAR is to provide a concise summary and independent assessment of the grant project in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions. The IAR is organized into the following sections:

- Introduction
- Objectives
- Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology Assessment
- Appendices
  - Appendix A: Final Report (under separate cover)
  - Appendix B: Awardee Rebuttal to Independent Assessment (awardee option)

For more information on the EISG Program or to download a copy of the IAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049, or email at:
eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/research/index.html.

# Distributed Generation Drivetrain For Windpower Application

## EISG Grant # 00-11


| | |
|---|---|
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**Introduction**

Contemporary wind-turbine design requires a new type of high-torque, low-speed drivetrain. Conventional drivetrains gear the slow rotation speed of the rotor shaft up to the significantly higher rotation speed of the electrical generator. The trend has been toward larger diameter, slower rotating wind turbines because rotor-blade rotation rate is limited by blade-tip speed. In larger and more powerful wind turbines, the stress exerted on the gear teeth becomes excessive. Figure 1. illustrates the massive size of modern wind turbines and should help the reader appreciate the magnitude of the forces at work in this application. Gear failure is common and significantly increases costs for operators. Until this problem is overcome, larger and more cost-effective wind turbine designs are likely to remain on the drawing boards.

Figure 1. A modern GE wind turbine under construction is illustrated. Note the technician at work standing within the rotor hub assembly. Completed in 2002, this proto-type is rated at 3.6 MW. Its turbine diameter is 341 feet and it sweeps an area of 91,439 square feet.

The elimination of this problem will allow the design of larger, more efficient wind turbines. Existing designs will benefit from lower costs for maintenance and drivetrain replacement. Reduction of turbine downtime will result in higher average power generation from wind farms, increasing their profitability, and lowering the cost of wind-generated electricity. The researcher projected that this drivetrain would cost 35-50% less than those it replaced and would reduce the cost of wind-generated electricity by as much as 15%.

The researcher proposed a distributed-generation drivetrain (DGD) as an alternative to conventional gearbox designs for large-diameter, high-torque wind turbines. This gearbox consists of an input-shaft-driven bull gear that drives a number of pinions around its periphery. These pinions divide the input torque load at its highest point, at the low-speed end of the drivetrain, thereby reducing gear tooth stress. Each pinion gear drives a relatively small generator. Figure 2. shows a computer-generated representation of the Distributed Generation Drivetrain under study.

This project focused on the control element of the distributed-generation drivetrain. Controls development focused on generator torque load modulation using voltage variation. The researcher measured the generators' torque-speed curves at varying voltages, assessed pushover characteristics, and applied the data to the design of control elements. The researcher then added these control elements, wrote codes for actuation, and tested the controls system to quantify its capabilities. The research characterized each of the generators on the dynamometer and assessed load sharing. Equipment for this program included a lab-scale gearbox (5 x 0.5kW squirrel cage induction generators) and a small (<5kW) dynamometer. A 480 V three-phase AC power source fed this equipment. Sophisticated laboratory control and data acquisition systems measured all significant generator characteristics.

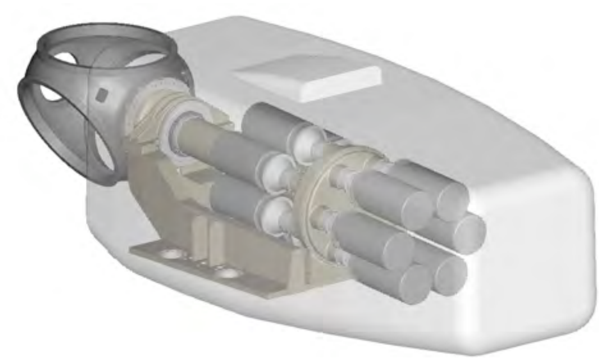

Figure 2. This computer generated representation of the Distributed Generation Drivetrain shows a configuration where the shaft torque from the rotor is divided to drive 12 smaller generators.

**Objectives**

The goal of this project was to determine the feasibility of employing three to five distributed generators in a single wind-turbine drivetrain. The researchers established the following project objectives:

1. Demonstrate that the gearbox functioned mechanically at acceptable efficiency
2. Design and build a test platform for controls development, including a dynamometer
3. Demonstrate that multiple generators would share the load equally
4. Investigate potential electrical efficiency improvements
5. Demonstrate overall functionality and viability of the DGD system
6. Demonstrate that induction generators can remain invulnerable to pushover at reduced stator voltage and with 10% speed increase for gust absorption.

**Outcomes**

1. The researcher successfully constructed fully operational lab-scale DGD and control systems. The researcher ran this equipment over 40 hours. Skilled gear designers for large-scale units have estimated the efficiency characteristics of the commercial-scale DGD to be similar to presently used systems (97-99% efficient).

2. The researcher built a test stand and lab-scale dynamometer and instrumented them to accurately control the DGD drive motor and measure the characteristics of individual generators.

3. The researcher mounted three Potencia poly-phase induction generators to the DGD and electrically connected them to the three-phase power mains using individual circuit breakers. The researcher conducted tests to measure the degree of intrinsic load sharing and the degree of torque modulation resulting from stator voltage reduction of an individual generator. The generators shared loads equally to within 0.6% at full load.

4. The researcher did not investigate potential electrical efficiency improvements because it was determined through analysis this was not appropriate to a lab-scale unit. Therefore the researcher did not design the prototype to investigate mechanical-electrical efficiency or to quantify vibration and noise under load. However, the manufacturer reported generator efficiency to be 99%, and the researcher verified this number. Gearbox efficiencies for commercial-scale gearing are expected to be in the range of 97% to 99%.

5. The researcher measured generator torque speed curves and assessed the effects of stator voltage modulation upon these curves. The researcher built and tested an electronic control system to demonstrate the electronic, dynamic control of induction generator stator voltage.

6. The researcher tested pushover torque characteristics on a dynamometer test stand with the generator under test directly coupled to the drive motor via a torque transducer. The researcher collected data on pushover torque versus stator voltage. The data show the technique of stator voltage control is sufficiently robust to maintain a 15% margin below pushover when the generator is operating at maximum speed limit. The researcher assessed this relatively small margin as adequate when coupled with variable rotor-blade pitch actuation.

**Conclusions**

1. Construction of a commercial-scale DGD system appears to be feasible. Test data validates the DGD concept when used with induction generators. The PA believes this project developed a viable means of control for a multi-generator DGD system that may be implemented in future commercial-scale equipment.

2. The chosen controls development platform worked well. However, there are new control software development platforms being introduced. The researcher should revisit the selection of development software.

3. The control scheme is a valid method of torque-controlling, squirrel-cage induction generators and offers a viable means of system control capable of achieving many of the goals of variable-speed wind-turbine systems.

4. Three-phase induction generators can be manufactured to conform to a narrow specification for torque matching with minimal cost impact. Designs that embrace the DGD concept can utilize off-the-shelf generators without special pre-screening and/or torque matching.

5. This project showed that efficient, three-phase induction generators can be manufactured to maintain pushover torque margins greater than 15% of full load during high-slip, low-

stator-voltage gust mitigation. This means that stator-voltage modulation can be employed to manage maximum torque limiting while still maintaining safe limits of pushover torque.

6. The use of SCR-T elements to control generator stator voltage is an effective method of torque control, but may introduce unwanted power-quality effects on the grid being fed. In a reactive electrical system, current spikes caused by switching transients will increase harmonic content. Increased harmonic content lowers efficiency and can cause interference with other electrical equipment. Capacitive filtering can reduce the effects, but the actual amount of capacitance and other filtering required to conform to IEEE 519 (wind-turbine power quality) has not been determined. Further work is required in this area.

7. The researcher is continuing to test other capabilities of the DGD, including efficiency gains attributable to incremental generator engagement and stepped variable speed through the use of multi-pole induction generators. This work is continuing under subcontract to DOE through the WindPACT program. The researcher will continue to assess issues such as over-current during voltage modulation and cost comparisons to other control techniques.

**Recommendations**

The PA recommends that CEC proceed with funding of the 1.5MW commercial-scale DGD under the presently awarded subcontract through the Sacramento Municipal Utility District. In addition, this work has continued under subcontract to DOE through the WindPACT program.

After taking into consideration: (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow-on funding within the PIER program.

Receiving follow-on funding ultimately depends upon: (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

**Benefits to California**

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply system. Using the 2007 California Air Quality Standard for combustion generators, 10,000 MW of wind turbine capacity generating 35 billion MWh of electricity will eliminate the release into the atmosphere of over 1.2 million tons of $NO_X$, 1.75 million tons of CO and 350,000 tons of volatile organic compounds.

The DGD is forecast to reduce the cost of wind-generated electricity by more than 0.5¢/kWh in Class 6 wind sites. The reduction in wind turbine cost of energy equates to gains in the profitability of wind developments and expands deployment into lighter wind areas, potentially enabling the large sector growth projected by the Department of Energy. This technology could enable as much as 10,000 MW of new wind-capacity installation in California over the next 20 years. This installed capacity will cost roughly $10 billion and will yield as much as 35 billion kWh of clean, renewable energy to the state.

## Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

### Marketing/Connection to the Market

The DGD is an integral component of the Clipper Quantum Technologies portfolio and is highlighted in that company's business plan. The DGD was featured in a company-published marketing brochure for investors.

### Engineering/Technical

The California Energy Commission, through its contract with SMUD, has awarded a $1.3 million contract to develop a commercial-scale prototype of the DGD. The progress made in the present study is being integrated with other power-train controls concepts towards the goal of testing this equipment in the second half of 2002.

### Legal/Contractual

Dehlsen Associates has been awarded a U.S. Patent for the DGD concept and has filed international patents in roughly two-dozen countries. It has licensed the DGD to Clipper Windpower Technology, Inc. for commercialization in wind-energy equipment and to Aquantis, LLC for production as a component of ocean-current turbines.

### Environmental, Safety, Risk Assessments/ Quality Plans

There is no specific mention of existing quality plans. However, the researcher is aware of the need for Quality, and is taking steps to address this need. Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental**.**

**Production Readiness/Commercialization**

The next phase of development will focus upon fabrication of a single commercial-scale gearbox for testing. As a part of this process, the researcher is designing to international engineering standards and integrating a rigorous quality control processes. The researcher plans to add a manufacturing engineer to staff.

## Appendix A: Final Report (under separate cover)

## Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

Appendix A to IAR 00-11

# ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

## EISG FINAL REPORT

## DISTRIBUTED GENERATION DRIVETRAIN FOR WINDPOWER APPLICATION


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PIER Subject Area: Renewable Energy Technologies

## Legal Notice



Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

## Acknowledgements

*The authors would like to thank the California Energy Commission for the support of this project, and for its continued support of future American windpower products and project developments.*

*We would also like to acknowledge the assistance of Andy Milburn of Milburn Engineering of Seattle, Washington, Bill Erdman, controls and power electronics consultant, and Carlos Gottfried of Potencia Industrial of Mexico City.*

*This research is being continued and extended under sub-contract from the National Wind Technology Center's WindPACT program. These results will be applied to a commercial scale prototype to be developed, under subcontract to the Sacramento Municipal Utility District (SMUD) through the California Energy Commission's PIER program, for testing in 2002.*

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## Abstract

This research investigated controls for a novel gearbox for large diameter, high torque wind turbines. This gearbox consists of an input shaft-driven bull gear that drives a number of pinions around its periphery. These pinions, which divide the input torque load at its highest point, thereby reducing gear tooth stress, each drive small generators. Equipment for this program included a lab scale gearbox (5 x 0.5kW squirrel cage induction generators) and a small (<5kW) dynamometer. This equipment was fed with 480 V three phase AC power, and a sophisticated system control and data acquisition system was added to measure all significant generator characteristics. Controls work focused upon generator torque load modulation using voltage variation. Each of the generators was characterized on the dynamometer, and then load sharing was assessed using the gearbox. The generators' torque-speed curves were measured at varying voltages, pushover characteristics were assessed, and data was applied to the design of control elements. These control elements were then added, the codes were for actuation, and the controls system was tested. Generator characteristics were assessed and capabilities of the control system were quantified.

# Executive Summary

## INTRODUCTION

- Contemporary wind turbine design is creating demand for a new type of high-torque low-speed drivetrain. The DGD (Distributed Generation Drivetrain) has been proposed by Dehlsen Associates, LLC as an alternative to conventional designs. Plans for commercialization of the DGD are underway by licensee Clipper Windpower Technology, Inc. (wind turbine application) and Aquantis, LLC (ocean current application).
- A lab scale DGD prototype has been built and tested. The test results and project conclusions are presented.

## PROJECT OBJECTIVES

- Investigate practicality of DGD concept as applied to large-scale wind turbines.
- Develop controls development platform for future work.
- Develop and test electronic induction generator torque control hardware, including assessment of load sharing between multiple generators.

## PROJECT OUTCOMES

- The lab scale DGD and control systems were successfully constructed, and are fully operational. Over 40 hours of run-time were logged on the equipment.
- A lab-scale dynamometer was built to accurately measure characteristics of individual generators.
- Load sharing between multiple generators was assessed. Data and discussion of this data are presented in **Appendix B**.
- Generator torque speed curves were measured, and the effects of stator voltage modulation upon these curves were assessed. Data and discussion of this data are presented in **Appendix B**.
- An electronic control system was built and tested. This system demonstrated that induction generator stator voltage can be dynamically electronically controlled.
- The effects of voltage modulation on pushover torque margin were assessed. Data and discussion of this data are presented in **Appendix B**.

## CONCLUSIONS

- No roadblocks appear to exist to the construction of a commercial scale DGD system. Promising test data validates the DGD concept when used with induction generators. We believe that we have developed a viable means of control for the multi-generator DGD system, which may be implemented in future commercial-scale equipment.
- Our control scheme is a valid method of torque controlling squirrel cage induction generators, and offers a viable means of system control capable of achieving all goals of variable speed wind turbine systems.
- The chosen controls platform (Labview RT) is ideal as a controls development platform for future wind turbine systems.

## Recommendations

- We recommend that CEC proceed with funding of the 1.5MW commercial-scale DGD under the presently awarded subcontract through the Sacramento Municipal Utility District. Dehlsen Associates feels strongly that this represents a direct path to rapid commercialization of this promising technology.
- We are proceeding to test other capabilities of the DGD. This work is continuing under subcontract to DOE, through the WindPACT program. We expect this effort to conclude before the end of 2001.

## Public Benefits to California

- The DGD is forecast to reduce the cost of wind-generated electricity by more than $0.005/kWh in Class 6 wind sites. In today's energy market with existing wind equipment, this cost reduction will move wind even closer to being the most desirable form of electricity generation available.
- The reduction in wind turbine cost of energy equates to gains in the profitability of wind developments, and expands deployment into lighter wind areas, potentially enabling the large sector growth projected by the Department of Energy.
- This technology may be enabling to as much as 10,000MW of new wind capacity installation in California over the next 20 years. This installed capacity will cost roughly $10 billion, and will yield as much as 35 billion kWh of clean, renewable energy to the state.
- Clipper Windpower, the licensee of this technology, is located in Santa Barbara, California. As this technology expands and becomes a part of Clipper's Quantum Turbine planned for release in 2005, this company will employ hundreds of Californians and will produce significant taxable income for the state.

# EISG Final Report

**INTRODUCTION**

In order to be cost competitive with combustion technologies, the wind industry has strived to evolve its technology, producing larger and larger wind turbines. To date, this effort has been very successful, reducing the levelized cost of energy from around $0.13/kWhr in 1980 to $0.04 in 2000. However, the wind industry is quickly accepting that a significant technical challenge exists for further rotor diameter growth: a cost-effective speed-increasing gearbox.

In most commercially available wind turbines, the rotor blades spin at a relatively low speed while the generator spins at a significantly higher rate. To couple the two systems, a speed-increasing gearbox is generally applied. For small turbines, speed-increasers were inexpensive, lightweight, and generally reliable. As turbines have grown, manufacturers have been forced to resort to heavy, tight tolerance, custom-made gearboxes whose problems have plagued the industry, recently resulting in near financial ruin for several major industry players[1]. The problem has principally been gear tooth loading. Reliability and maintenance issues that have emerged with larger turbines represent a major challenge to the industry, forcing it to seek new solutions.

The focus of the present project, the Distributed Generation Drivetrain (DGD) (see **Figure 1**), provides a solution to this problem by dividing the torque loads where they are highest, at the low speed end of the powertrain. The rotor shaft drives a large

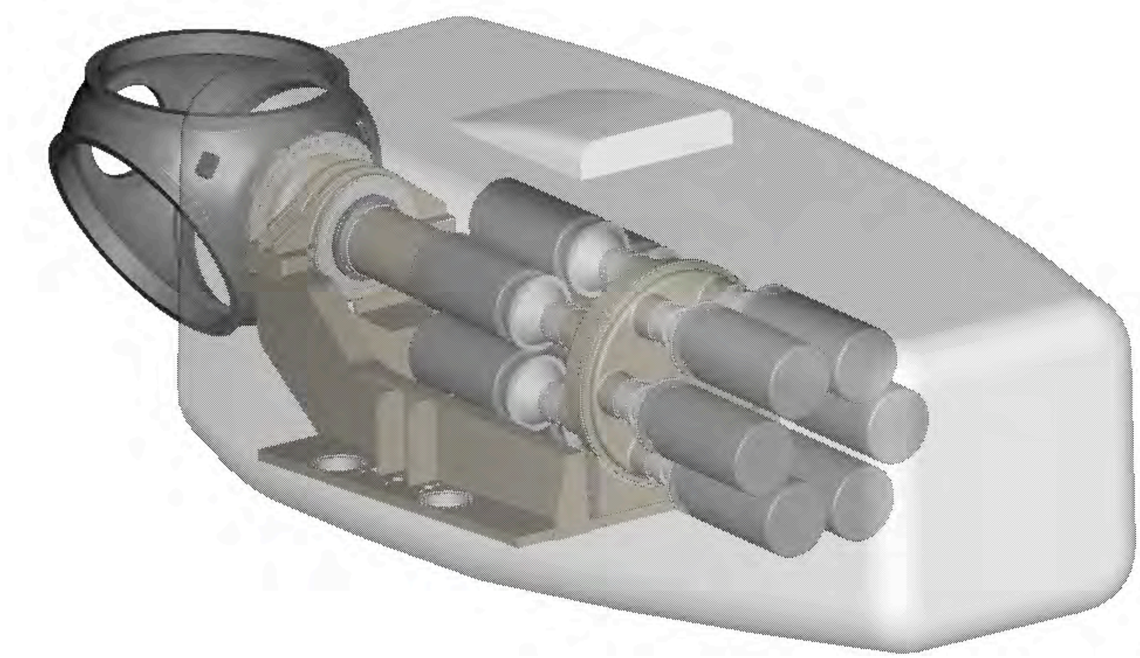

**FIGURE 1. The Distributed Generation Drivetrain design positions multiple generators around the periphery of the rotor shaft-driven bull gear.**

[1] NEG Micon was recently forced to the edge of bankruptcy as a result of 600 failed gearboxes. Many other manufacturers, including Vestas and Enron Wind Corp., have reported gearbox difficulties with significant associated costs.

bull gear, which in turn drives multiple pinions. Because the load path is split at the low speed end, the gear tooth loading is greatly reduced. In other words, because multiple pinion-bull gear interfaces are working in concert, the perimeter of the bull gear is much more effectively used. The U.S. patent office issued Dehlsen Associates patent protection (U.S. 6,304,002, 31 claims) for this design on October 16, 2001.

Gear tooth loads not only drive gearing initial and life-cycle costs, but also affect the costs of bearings, shafts, and the gearbox housing. Cost estimates performed by Clipper Windpower Technology, Inc. (Dehlsen Associates' windpower technology subsidiary and licensee) indicate that this powertrain will cost 35-50% less than present designs, and will have significant additional lifecycle and productivity benefits, totaling as much as a 15% reduction in the cost of generated electricity. These estimates have recently been confirmed by independent studies performed for the U.S. DOE under its WindPACT component analysis program[2].

Beyond the cost savings, each sub-powertrain is designed using commercially available components that are significantly less massive than conventional monolithic powertrains. One goal of the DGD design is to constrain sub-powertrain weights to a level where they may be handled without heavy lifting equipment. Compared with conventional powertrains, this represents a substantial advantage in an O&M context, where gearbox and generator handling significantly affects lifecycle costs. Each nacelle may be fit with its own small winching system to lower these components to the ground, in the case of needed replacement, without use of large and costly cranes. In present systems, component remove and replace operations routinely cost in excess of $150,000 (roughly 10% of the cost of a new installed turbine), not including the cost of the component itself.

A second additional advantage of the DGD is the decrease in down-time for a turbine. If a DGD contains ten sub-powertrains and a sub-gearbox fails, the control system can switch the sub-powertrain off, de-rating the turbine power by 10% but continuing to operate with the remaining 90% of capacity until maintenance can arrive. Because the mean operating load of a turbine is around 40%, and because the tenth generator is online only 8 to 15 % of the year, this de-rating is expected to have little effect when applied for the short periods required for part repair or replacement.

Another advantage of the DGD is the ability to incrementally bring sub-powertrains on-line. For instance, a turbine may operate with five of the ten sub-powertrains when wind velocities are lower. This allows each generator to work at near its rated power, improving the net generation efficiency of the system.

The power and control side of the DGD takes the mechanical output from the individual second-stage gearboxes and produces 3-phase electrical power to the utility line. To perform successfully, this system must

1) assure a uniform torque load distribution between generators;
2) smoothly connect and disconnect with the utility line;
3) seek maximum operating efficiency
4) monitor and provide protection for mechanical and electrical parameters operating out of specification; and
5) accommodate input from external systems and operators.

[2] Study performed under DOE contract by Global Energy Concepts of Seattle, Washington.

Therefore, besides generators, the DGD power conversion system requires an appropriate controller to manage these tasks.

This program investigated a specific generator configuration and control system design, incorporating an embedded, real-time controller orchestrating control tasks with a host computer linked to it via a high-speed network. In this design, the host acts as the data-logging device and serves as the user interface, thus freeing the controller to attend to time-critical control functions without distraction. The host stores dynamic performance data to disk while its keyboard, mouse and display provide the operator with real-time status and the ability to initiate commands to the controller.[3]

Induction generators are used for mechanical-electrical power conversion on the prototype DGD. Induction units were selected due to their low cost and suitability in a wind turbine loads environment.[4] Five 0.5 kW generators are configured in parallel on a 480 Volt AC circuit (240 Volt line with transformer); arranged as such, each generator operates at 480 Volts (nominally) and the current from each sums to produce the total current output. If the torques are balanced the current output from each generator is equal, making the prototype's total current equal to five times the output of a single generator. Ultimately the existence of these five generators is transparent to the line as it sees only a single, three-phase output.

An inherent problem with induction generators is the difficulty in manufacturing them on a standard production line to have precisely repeatable slip characteristics. In other words, by design, induction generators run faster than synchronous speed by some small percentage (approximately 1.5% at full load) known as slip, but from one unit to the next, this slip varies by a small amount (nominally plus or minus 0.2%). On a 1800 RPM design this amounts to a possible variation of 7.2 RPM between generators with a nominal full slip range of 27 RPM; since the power output goes from zero at 1800 RPM to full load at 1227 ± 3.6 RPM, this slip variability has a huge impact on the load sharing of generators all being driven at exactly the same speed. Before the present project was proposed, several generator manufacturers were consulted regarding this variability, with different responses as to the extent to which improved quality control has alleviated this issue. Thus, one of the focal points of this study was to quantify the variability of modern induction generators, and to compare measured results to manufacturer predictions. Potentially, the system may require a DGD control function to regulate the torque on each induction generator and to assure that the torques are balanced between generators at any given system load.

Various techniques of torque control for the DGD have been considered by DA in the course of development, including both passive and active control methods; six concepts have been filed with the U.S. Patent Office.

The concept investigated under the present CEC funding is based on stator voltage modulation in induction squirrel cage generators. The preferred implementation of this idea utilizes Silicon Controlled Rectifiers (Scrs) and parallel-connected

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[3]Note that when installed on a wind turbine, this control system will be integrated into the turbine's controller.

[4] Synchronous generators were also considered, but historically have been less successful than induction units on wind turbines due to problems of speed control in a gusting winds, and the requirement that the prime mover exactly match synchronous speed; nonetheless, future development may include synchronous machines with better control strategies.

transformers to control generator voltage, allowing active control of torque at all power levels (see line diagram in **Appendix B, Figure B1**). A full range of operational performance was evaluated with this control approach, first assessing the impact of voltage variation using a Variac, and then implementing SCR-T control elements. The additional advantages provided by active control such as soft-starting and over-torque protection were also investigated.

### PROJECT OBJECTIVES

The goal of this program was to demonstrate the successful operation of the first, distributed generation drivetrain prototype under dynamometer test conditions. Inherent in this objective was to prove the basic mechanical function of the gearbox, and to prove the overall functionality of the control system. The present configuration is designed to quantify general characteristics of a generator/controller, while allowing for assessment of load sharing between individual generators.

As stated in the application for this program, our five goals were:

a) Prove mechanical function of the gearbox
b) Develop suitable test platform for controls development
c) Assess load sharing capabilities between generators
d) Investigate potential-electrical efficiency improvements
e) Prove overall functionality and viability of system
f) ***New Objective:*** *Asses vulnerability of induction generator to pushover in region III at reduced stator voltage.*

Prior to contract completion for this work, we re-assessed our design based upon the opinions of experienced gearbox designers.[5] Following their input, it was decided that objective (d) was not relevant to a lab-scale unit, and therefore, the prototype was not designed to investigate mechanical-electrical efficiency, or to quantify vibration and noise under load.

The new objective was added because induction generators have a characteristic called pushover, wherein when slip exceeds a limit, the generators' ability to take torque decreases with increasing speed. This is of high concern to wind turbines, as this will result in a turbine fault, if not a rotor over-speed condition. In region three, where torques are maximum, generators are typically designed to have pushover margins of 2.4 to 3.0 times rated torque. However, when voltage is reduced, the pushover torque is also reduced. In region 3, where torques are highest and where we aim to use voltage modulation to achieve gust adsorption, pushover is therefore of high concern. A typical turbine design would require a 5% to10% speed increase for gust absorption.

### PROJECT APPROACH

The basic approach of this program was to quantify characteristics of three phase induction generators and to assess the controllability of these generators individually through modification of their stator voltage levels. Once the generators' characteristics

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[5] Both Milburn Engineering of Seattle, Washington and Powertrain Engineers of Penwaukee, Wisconsin have indicated that commercial-scale DGD efficiency should exceed 97%, and will more likely approach 98-99% for the bull gear-pinion gear pass.

were detailed, they could be assembled onto a lab-scale DGD gearbox, where the generators' shaft speeds would be precisely coupled. The operating characteristics of the generators could then be assessed as a group. A PXI controller from National Instruments was applied as a data acquisition and collection device, and as a means for precisely controlling elements of the system.

**FIGURE 2: The lab-scale DGD test stand.**

Components of this system, manufacturers and approximate costs are detailed in **Appendix B, Table B1**.

The lab-scale DGD gearbox (see **Figure 2**) designed and fabricated for this project was well oversized for the loads we applied. The design load of the generators totaled 2.5kW, while we estimate that the gearing and housing could bear loads 20 times as great. This was selected such that larger loads may be applied in the future, and because it was much less expensive to provide reduced engineering analysis and larger structures than the reverse in the case of a single, small-scale unit. In addition, the system is driven from a pinion shaft instead of from the center of the bull gear, as would be found in a wind turbine application. This was done so that an 1800 rpm drive could be used to drive 1800 rpm generators without the need for additional small gearboxes, flanges and couplings. This means that, while the wind turbine DGD bull gear would revolve near 20 rpm, the test unit bull gear turned near 300 rpm. The net effects of the oversized gearing and high speed of the bull gear are increased gearbox noise and reduced gear efficiency. Skilled gear designers for large-scale units have reasonably estimated the efficiency characteristics of the commercial-scale DGD to be similar to presently used systems, or 97-99% efficient.

When the DGD, controller, and drive motors arrived, the system was assembled and a spin test was performed using one 3kW motor as a system driver and one to provide load as a generator. During these tests, a modest amount of localized heat was

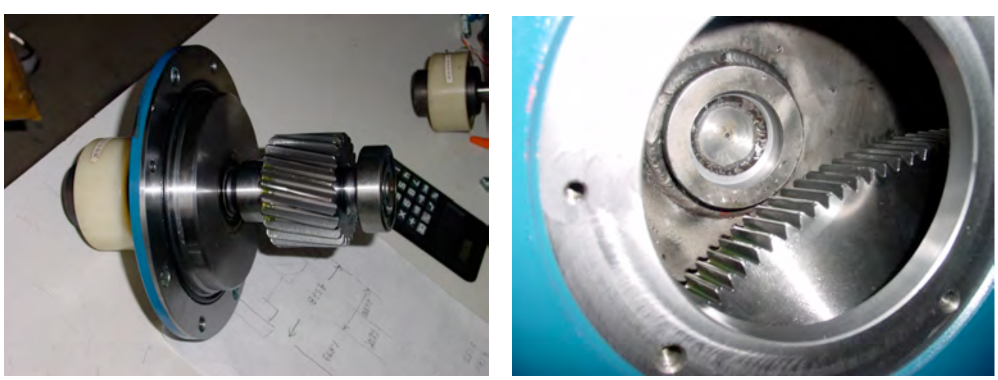

**FIGURE 3: One of the pinions (left) on the lab-scale DGD was disassembled, the bull gear and bearing seats (right) were examined, and the bearings and pinion were reassembled.**

detected in the proximity of one of the pinions. In response, the gearbox oil was drained, the pinion and bearings were removed and reseated (see **Figure 3**), the oil was replaced, and the spin test was repeated. No localized heat was detected after operating the system for approximately 20 minutes.

Factory calibrated special test equipment was purchased, as well as a complete set of real-time computerized control hardware. Labview software control programs were written, and individual generators were characterized and compared to factory dynamometer data.

Three of the Potencia poly-phase induction generators were then mounted to the DGD and electrically connected to the three phase power mains using individual circuit breakers for each generator (see **Appendix B, Figure B1**). Tests were conducted on the DGD to measure the degree of intrinsic load sharing, and the degree of torque modulation resulting from stator voltage reduction of an individual generator. The stator voltage reduction was implemented using a motorized variac, a special type of adjustable transformer which allows for reduced voltage output while maintaining power quality. Test results are shown in **Appendix B, Figure B3**.

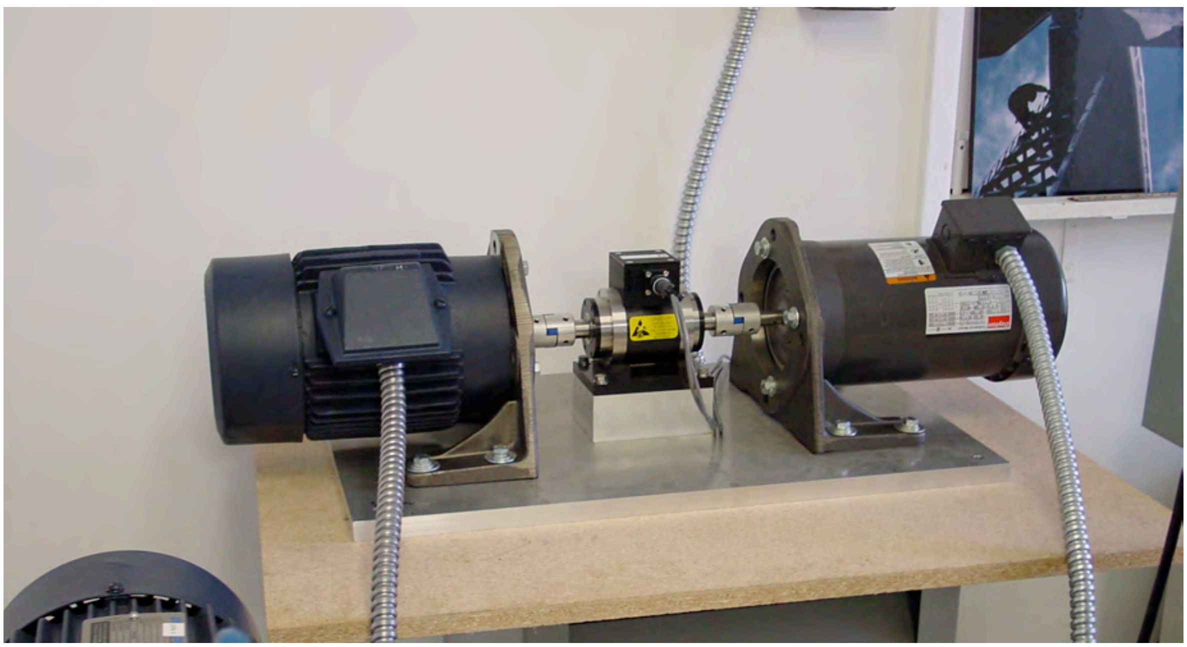

**FIGURE 4. Dynamometer test stand**

Pushover torque testing was accomplished on a dynamometer test stand (shown in **Figure 4**) where the generator under test was directly coupled to the drive motor via a torque transducer. Pushover torque versus stator voltage test results are shown in **Appendix B, Figure B3**.

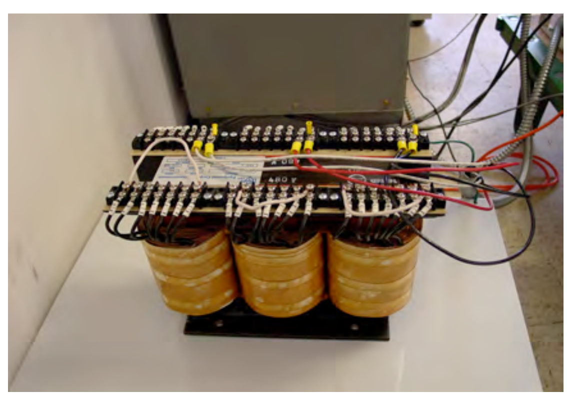

**FIGURE 5: SCR-T reactor**

FIGURE 6a: Real-time control console

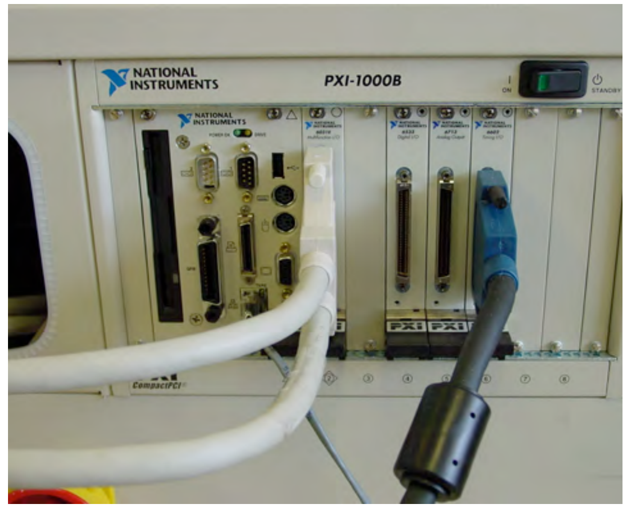


FIGURE 6b: Console close-up

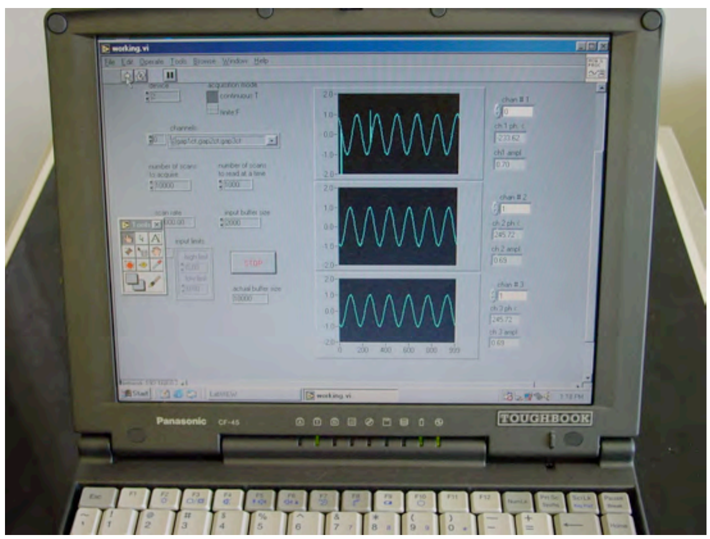


FIGURE 7: Labview Control front panel screen

Utilizing the generator voltage vs. torque parameters found during the torque modulation testing, a special reactor transformer with multiple taps on the primary and secondary was designed and constructed to test the SCR-T stator voltage control concept. The SCR-T control method was compared to the Variac method on the dynamometer test stand. The SCR-T reactor test results are shown in **Appendix B, Figure B5**.

The SCR-T reactor is shown in **Figure 5.**

## Project Outcomes

All objectives (with the exception of stricken objective (d) ) of this project have been met. Results strongly encourage further development of the DGD as a commercial product for wind turbines. A detailed discussion of the project outcomes is presented in **Appendix B**.

## CONCLUSIONS AND RECOMMENDATIONS

1. Construction of a reliable DGD gearbox is feasible, and may include readily available parts and materials. Analyses by outside parties under contract to DOE now confirm that this design may be the lowest cost alternative for high torque wind applications of the future.

2. DGD controls hardware and software currently available from National Instruments is readily available and is not unduly complex. In addition, recent announcement of new control hardware products (such as Fieldpoint 2000) may offer significant future cost savings.

3. The goals of this project have been met. These findings and further finding, as presented in **Appendix B**, strongly encourage further development of commercial scale equipment.

## PUBLIC BENEFITS TO CALIFORNIA

Although much of the crisis appears to have passed, California's recent power shortages and fuel price spikes are symptoms of market imbalance and fuel price vulnerability (see **Figure 8**). In the 1980's California was the world leader in wind development, in essence creating many of today's industry leaders[6]. During the 1990's, however, continuing U.S. subsidies supporting competing forms of energy, coupled with Federal policies supporting fossil fuel dependency resulted in a global wind energy focal shift towards Europe. Even today, as wind is making a resurgence in the U.S., the majority of this development is occurring in Texas, the Pacific Northwest, and in the Great Plains states.

California presently has on the order of 1,600MW of installed wind capacity. When natural gas prices are low, as they were throughout the late 1990's, the cost of generated electricity may parallel the cost of modern wind-generated electricity[7]. However, windpower contracts typically fix energy sales prices for periods as long as 20 years, and are therefore completely fuel price-independent once they are installed. When the average price paid by a California residential consumer in 2000 was $0.093/kWh[8] and recent state actions have raised that price toward $0.15/kWh, long-term fixed price contracts may save the ratepayers hundreds of millions of dollars per year.

Our projected cost reduction of $0.005/kWh may prove enabling for future wind development. For a 100MW wind project, this reduction in COE equates to a

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[6] European companies such as Vestas were sustained solely by development in California during this period. Some California companies such as Zond (now Enron Wind Corp.) and SeaWest continue to exist, while others such as Kenetech and American Wind Turbines are remembered only by the expertise and technologies developed during this time which today's companies now leverage.

[7] Windpower presently costs approximately $0.04 per kWh in a class 6 wind site (8.5m/s at hub height). When the production tax credit ($0.015/kWh) is subtracted from this cost, the sales price of windpower is approximately $0.025/kWh.

[8] http://www.eia.doe.gov/cneaf/electricity/esr/esrt17p5.html

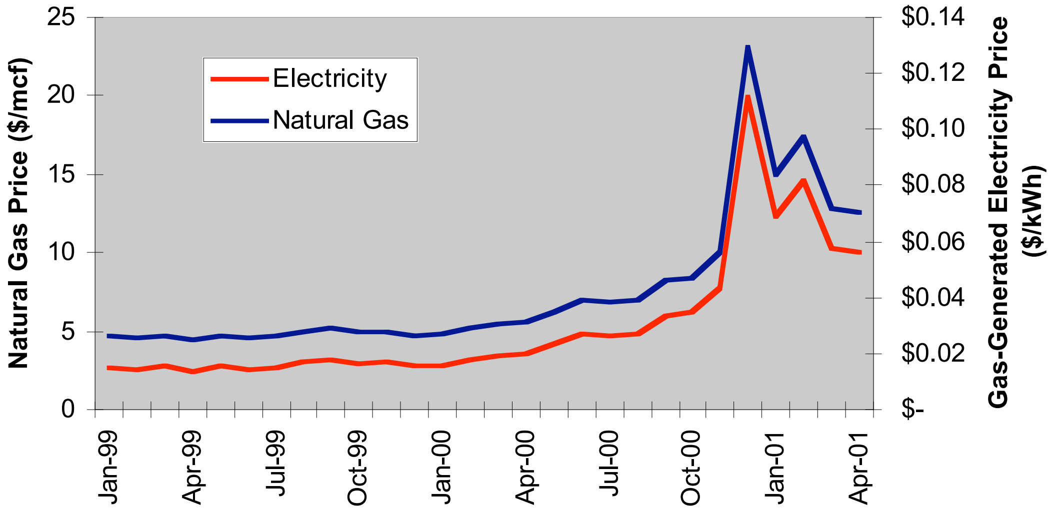



**FIGURE 8. Utility natural gas prices and associated cost of gas-generated electricity from January 1999 through April 2001.**

roughly $12.5 million gain in the project's net present value. Additionally, areas that are presently non economic due to lower wind will be open for development with a lower COE.

In 2000, 212 billion kWh were consumed in California, of which roughly 1.5% came from wind energy. Although savings cannot be realized on presently installed turbines, by the end of 2001, the U.S. will have added 2,500MW of new wind capacity. The U.S. DOE conservatively[9] projects that over 75,000MW of new wind capacity will be added nation-wide before 2020. While much of this development will continue to be focused in the Midwest, it is conceivable that as much as 10,000MW of new wind capacity could be added to the state during this period, generating as much as 35 billion kWh per year. Clipper Windpower is dedicated to making this windpower growth a reality, and is presently underway on a 180MW project being developed for the California Power Authority, and a 3,000MW project in the South Dakota called "Rolling Thunder".

The Clipper DGD will form the center of the Clipper 1.5MW Quantum Turbine, which is targeting a cumulative reduction in cost of energy of over $0.018/kWh (to below $0.020/kW in Class 6 winds) from today's most competitive equipment. We believe our portfolio of technologies presents real opportunity to achieve this mark, and that this COE reduction will prove enabling for wind turbine development to levels far beyond those predicted by DOE. In regions of the world where other forms of electricity are more expensive, such as northern Europe, windpower is already playing a dominant role. Denmark plans to provide more than 50% of its energy from windpower by 2020.

Lastly, Clipper Windpower Technology is a California company. While the company's DGD-containing wind turbines will be sold globally, it is anticipated that a significant portion of these turbines will be manufactured in California. Each 100MW of wind turbine generators produced will yield revenues of more than $100 million. With

[9] Some industry groups are projecting in excess of 300,000MW of new U.S. wind capacity during the same period, following expected reductions in cost of wind-generated electricity.

the forecast industry growth, the DGD promises to play a pivotal role in the growth of a company that may employ over 1,000 Californians before the decade is over.

## DEVELOPMENT STAGE ASSESSMENT

**TABLE 1. Development Assessment Matrix**

| Stages / Activity | 1 Idea Generation | 2 Technical & Market Analysis | 3 Research | 4 Technology Development | 5 Product Development | 6 Demonstrat-ion | 7 Market Transformat-ion | 8 Commercial-ization |
|---|---|---|---|---|---|---|---|---|
| Marketing | | | | | | | | |
| Engineering / Technical | | | | | | | | |
| Legal / Contractual | | | | | | | | |
| Risk Assess / Quality Plans | | | | | | | | |
| Strategic | | | | | | | | |
| Production. Readiness / | | | | | | | | |
| Public Benefits/ Cost | | | | | | | | |

From the outset of DGD development, we have focused on advancement of this technology for near-term commercialization. While we have not specifically focused on the activities shown in **Table 1** as described, we have made significant progress as follows:

**Engineering / Technical:** The California Energy Commission, through its contract with SMUD, has awarded us with a $1.3 million contract to develop a commercial-scale prototype of the DGD. The progress made in the present study is being integrated with other powertrain controls concepts towards the goal of testing this equipment in the second half of 2002.

**Legal / Contractual:** Dehlsen Associates has been awarded a U.S. Patent for the DGD concept and has filed international patents in roughly two dozen countries. We have licensed the DGD to Clipper Windpower Technology, Inc. for commercialization in wind energy equipment, and to Aquantis, LLC for production as a component of ocean current turbines.

**Marketing / Strategic:** The DGD is an integral component of the Clipper Quantum Technologies portfolio, and is highlighted in the company's business plan. The DGD is featured in a company marketing brochure for investors recently published.

**Production Readiness / Quality Plans:** The next phase of development will focus upon fabrication of a single commercial scale gearbox for testing. As a part of this process, we are designing to international engineering standards and we are integrating rigorous QC processes.  We are hoping to add a manufacturing engineer to our staff within the next 9 months.

**Public Benefits / Cost:** Our cost estimates showing the potential for significant cost savings have been independently confirmed by DOE contractors under the WindPACT program. Reduction in cost of energy is the benefit to the public both in reduced long-term and fixed price power pricing, and in the reduction of externalities associated with fossil-fuel burning generators.

## Appendix A: DGD run-time log data.

| Date | HP in | Gen loc (X) | % load | Time (min) | Time (hr) |
|---|---|---|---|---|---|
| 7/2/01 | 2.50 | A | 100 | 240 | 4.00 |
| 7/3/01 | 2.25 | A | 100 | 190 | 3.17 |
| 7/4/01 | | | | | |
| 7/9/01 | 3.00 | A,B | 80 | 60 | 1.00 |
| 7/10/01 | 3.50 | A,B,C | 50-100 | 20 | 0.33 |
| 7/11/01 | 3.00 | A,B | 100 | 300 | 5.00 |
| 8/7/01 | 2.50 | B | 100 | 120 | 2.00 |
| 8/9/01 | 2.75 | B,D | 75 | 80 | 1.33 |
| 8/10/01 | 3.20 | A | 150 | 300 | 5.00 |
| 9/6/01 | 3.20 | A,B,D | 120 | 180 | 3.00 |
| 9/10/01 | 3.20 | A,B,D | 120 | 200 | 3.33 |
| 9/12/01 | 3.50 | A,B, | 200 | 210 | 3.50 |
| 10/1/01 | 3.00 | A,B | 150 | 100 | 1.67 |
| 10/2/01 | 2.00 | A | 100 | 75 | 1.25 |
| 10/3/01 | 1.00 | A | 60 | 10 | 0.17 |
| 10/16/01 | 3.20 | A | 150 | 310 | 5.17 |
| 10/17/01 | 2.00 | A | 100 | 30 | 0.50 |

**Total Hours 40.42**

# Appendix B: Project Results

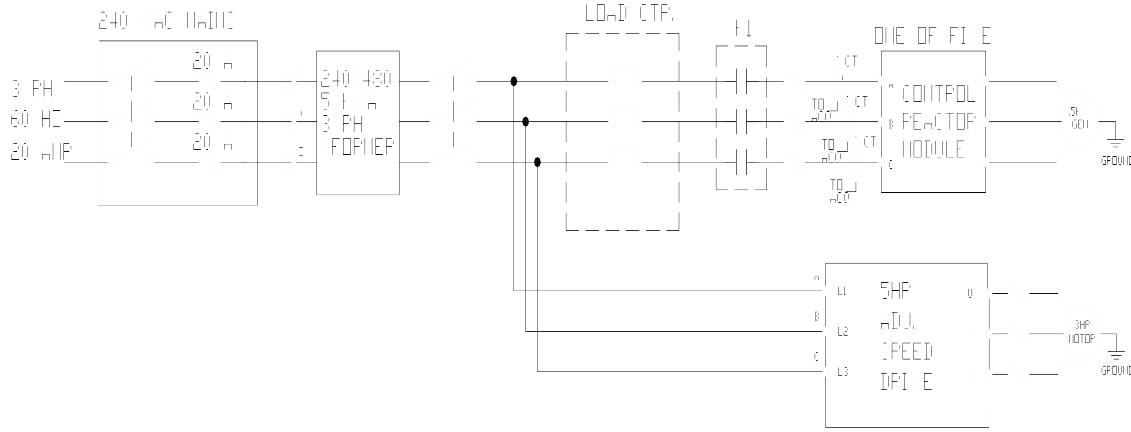


**FIGURE B1. Schematic of control system.**

| TABLE B1. System Components and Expenditures | | |
|---|---|---|
| **Item** | **Specs / Info.** | **Cost** |
| **Gearbox** | | |
| Design Consulting | Milburn Engineering | $ 8,134 |
| Housing | Kern Tech | $ 20,533 |
| Gears | Seattle Gear Works | $ 1,528 |
| Flange Adapters | Cascade Machinery | $ 405 |
| Other Hardware | Misc. | $ 2,203 |
| | total | **$ 32,803** |
| **Drive Systems** | | |
| Drive Motors (3kW) | Granger | $ 582 |
| Drive Motor (5kW) | Potencia Industrial | $ 920 |
| Variable Frequency Drive | Granger | $ 1,363 |
| | total | **$ 2,865** |
| **Generators** | | |
| Generators (0.5kW) | Potencial Industrial | $ 2,700 |
| | total | **$ 2,700** |
| **Data Collection Equipment** | | |
| Torque Transducer | Magtrol, Inc. | $ 4,760 |
| Optical Shaft Encoder | Encoder Products Co. | $ 750 |
| Isolated voltage Transducer | AYA Electronics | $ 560 |
| Current Transducers | AYA Electronics | $ 975 |
| Oscilloscope | Tektronix (Test Equity) | $ 3,295 |
| | total | **$ 10,340** |
| **Controls System** | | |
| Real Time Controller | | $ 17,080 |
| Laptop Computer | | $ 1,300 |
| Motorized Variac | | $ 1,600 |
| SCR-T Reactors | | $ 640 |
| SCR control electronics | Enerpro | $ 1,387 |
| | total | **$ 22,007** |
| | | |
| | **Equipment total** | **$ 70,715** |

## Project Outcomes

1. Proven DGD gearbox viability, reliability, and life. Over forty hours of running time at various load levels have been logged (Time log data in **Appendix A**). Although the test gearbox is greatly oversized for the loads of the present system, the design is fully functional and represents an outstanding platform on which to develop further controls in the future. Everything we have seen in our test program reflects positively on the prospects for future full-scale DGD development.

2. Test Stand and dynamometer development. The test stand and dynamometer are fully functional, including test instrumentation, power mains connections and National Instruments DAQ and Control system. These systems have been designed to be extremely flexible to facilitate future modifications. A functioning real-time data acquisition and closed-loop control system has been implemented

on the DGD test stand. Control system capabilities include measuring generator output power and drive motor speed, issuing speed change commands, programmatically controlling SCR-T's, and data logging. The control system is the ideal development platform for testing, and controls algorithms developed and tested in the system may be directly implemented into commercial equipment through the controller's compiler functionality.

3. Assess load sharing capabilities between generators. Induction generator load-share characteristics are shown in **Figure B2**. Excellent matching, within 0.6% at full load, was found among all six generators tested without any modifications. This is significant because it allows the gearbox pinions to be designed with only a very small increase in safety factor due to generator hogging. It also clearly demonstrates that load may be simply and successfully divided between the DGD's multiple paths, a contested issue prior to this research.

4. Investigate mechanical-electrical efficiency. Mechanical efficiency of the gearbox was not a part of the project study due to the gearbox design issues discussed above. Generator electrical efficiency was reported by the manufacturer, and verified by Clipper (see **Figure B6**). SCR-T efficiency, as expected, was found to be very high, nearly 99%. Gearbox efficiencies for commercial scale gearing are expected to be within the 97-99% range.

5. Fully functioning prototype DGD system, including SCR-T stator voltage control. A special purpose reactor and SCR control was designed and fabricated to test the efficacy of the SCR-T concept for induction generator torque modulation. The SCR-T system stator voltage modulation appears to be a viable method for smooth control of generator torque load.

6. Generator pushover torque test data (New Objective). The 0.5KW generators were tested on the dynamometer using a 3kW drive motor and a torque transducer. Multiple tests were run at voltages varying from 100% of nominal voltage (480V) through roughly 40% nominal (200V), as shown in **Figure B3**. The test data shows that in order to achieve a 10% speed increase (from 1848 to 2033 RPM) while maintaining the load torque at or below the full load limit, the stator voltage must be lowered to roughly 220-240 VAC, as shown in **Figure B4**. Pushover torque (from the 200 VAC curve) then becomes 4.12 Newton-Meters. Since the full load rating of the generator is 3.50 N-M, the generator will be operating at 85% of the pushover torque limit at maximum speed. This torque margin, while much lower than the margins at higher stator voltages, is felt to be adequate when combined with variable rotor blade pitch actuation.

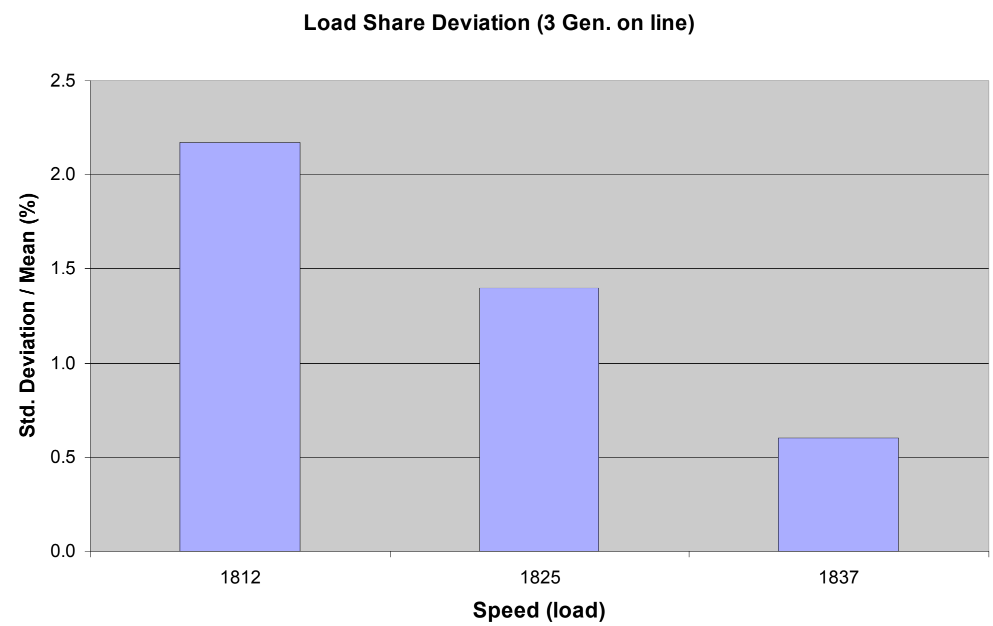



**FIGURE B2. Load matching between three generators run on the DGD is within 2.2% at low load and within 0.6% at full load.**

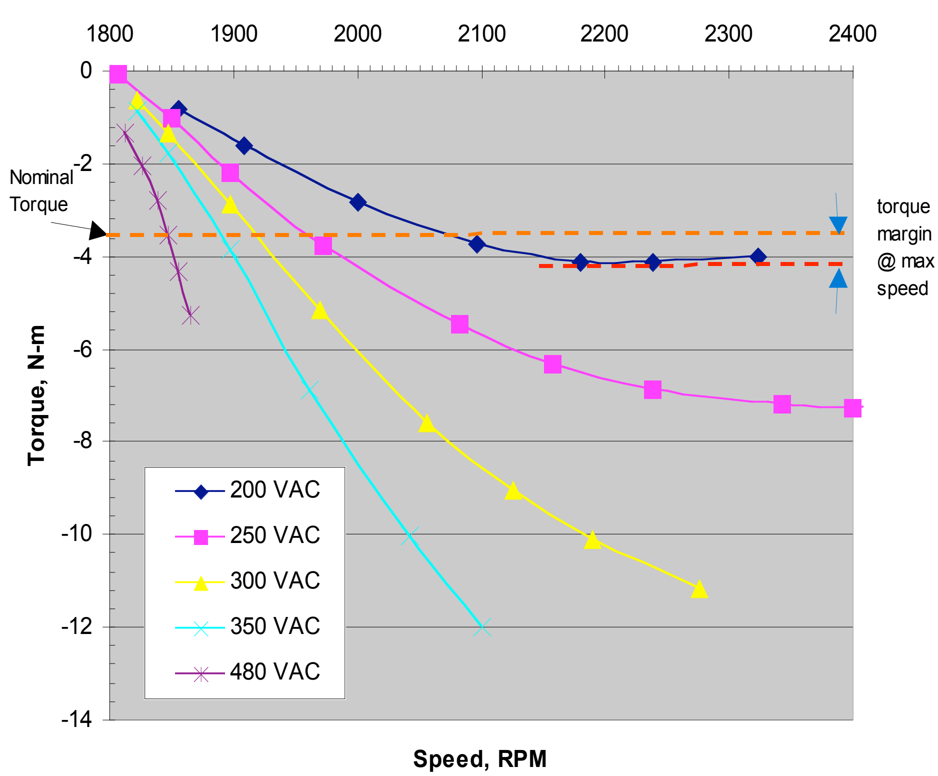



**FIGURE B3. Pushover torque safety margin assessment with voltage modulation.**

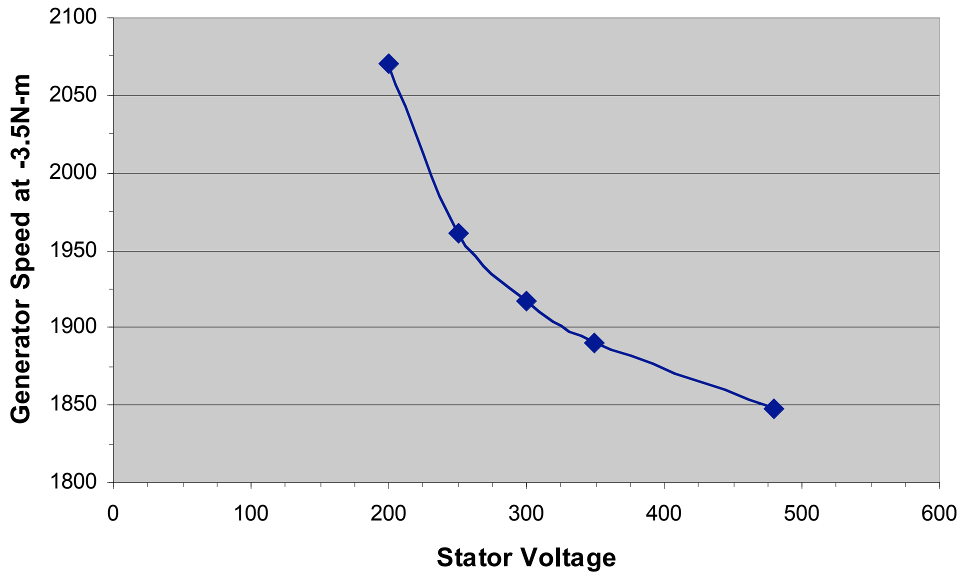



**FIGURE B4. Rated torque generator speed corresponding to stator voltage modulation.**

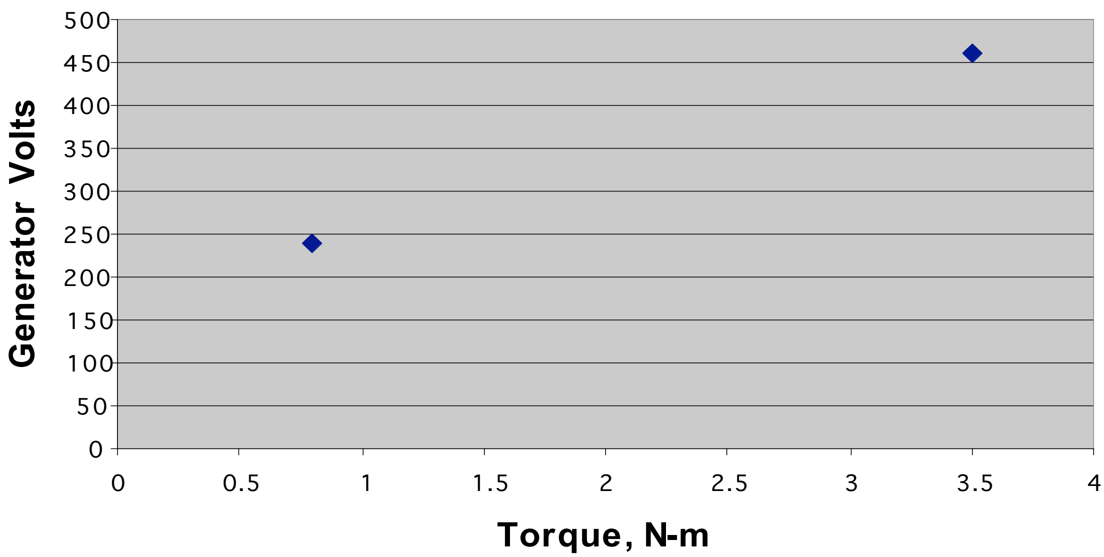
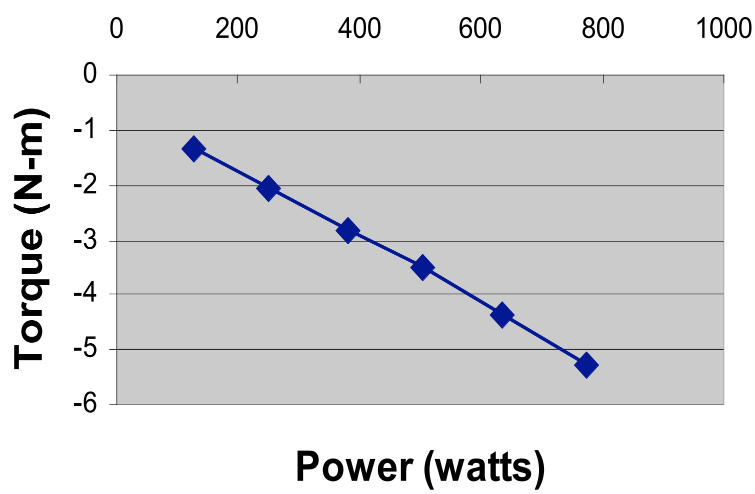



**FIGURE B5: Reactor test data.**

| Amps | Watts | RPM | Torque | Efficiency |
|---|---|---|---|---|
| | | | | |
| 0.742 | 125 | 1813 | -1.324 | 0.5 |
| 0.832 | 251 | 1826 | -2.06 | 0.64 |
| 0.95 | 380 | 1837 | -2.81 | 0.7 |
| 1.1 | 502 | 1848 | -3.52 | 0.74 |
| 1.23 | 636 | 1856 | -4.35 | 0.75 |
| 1.4 | 774 | 1866 | -5.26 | 0.77 |



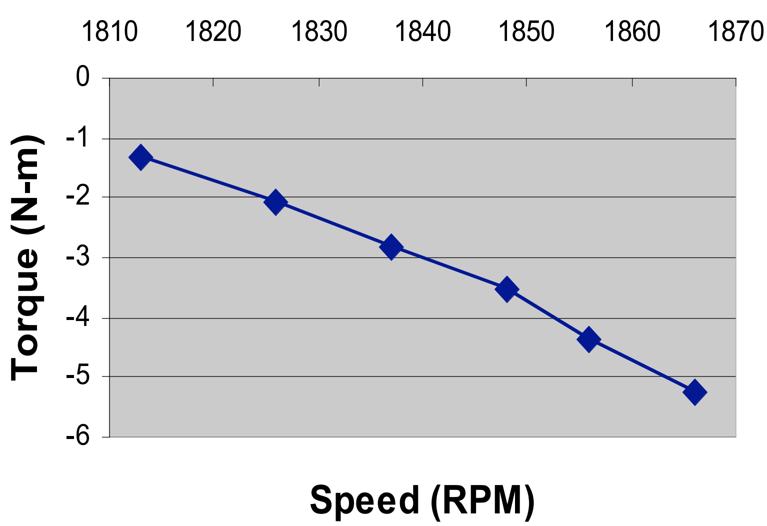




**Figure B6: Generator 8011 Test Data**

## Commercial Scale Cost Data

A preliminary assessment of cost to construct a 1.5 MW commercial turbine drivetrain is given below:

| | | |
|---|---|---|
| 1. | 1 ea. 1.5 MW DGD Gearbox @ $80 K | $80 K[10] |
| 2. | 12 ea. mid-range gearbox @ $3.0 K | $36 K[11] |
| 3. | 12 ea. 125 KW squirrel cage induction Generators @$3.0 K | $36 K[12] |
| 4. | 12 ea. 125 KW SCR-T reactors @ $ 0.9 K | $11 K[13] |
| 5. | 12 ea. 125 KW SCR-T power electronics hardware @ $1.25 K | $15 K[14] |
| 6. | 1 ea. Fieldpoint Real-time Control system | $ 4 K[15] |
| 7. | Misc. switchgear & sensors | $ 8 K |
| | Total = | $ 190 K |

For comparison purposes, presently available drivetrains (implementing doubly-fed generator with partial conversion) currently cost approx $300 K. (Gearbox = $170 K, Generator = $65 K, Control system = $65 K).

## Further Conclusions and Recommendations:

4. Three phase induction generators can be manufactured to conform to a narrow specification for torque matching with minimal cost impact. Designs that embrace the DGD concept can utilize off-the-shelf generators without special pre-screening and/or torque matching. (Ref. **Figure B2**)

5. Efficient three phase induction generators can be manufactured with design properties such that pushover torque margins greater than 15% of full load can be maintained during high slip, low stator voltage gust mitigation. This means that stator voltage modulation can be employed to manage maximum torque limiting, while still maintaining safe limits of pushover torque. (Ref. **Figure B3**).

6. The use of SCR-T elements to control generator stator voltage is an effective method of torque control, but may introduce unwanted power quality effects on the grid being fed. In a reactive electrical system, current spikes caused by switching transients will increase harmonic content. Increased harmonic content lowers efficiency and can cause interference with other electrical equipment. Capacitive filtering can be applied to reduce the effects, but the actual amount of capacitance and other filtering required in a particular DGD system in order to conform to IEEE 519 (wind turbine power quality) has not been determined. Further work is required in this area.

[10] Source – Estimate per **Power Train Engineering**., Penwaukee, Wis.
[11] 170 HP **Bonfiglio**li planetary gearbox
[12] Source - Estimate per Carlos Gottfried, **Potentia** Industrial S A
[13] **Mag-Tran** Eqipment Corp. Quote # F111201-B, High-efficiency 125 KW inductor, 480 volt, 3 phase.
[14] Based on estimate of $10.00 per KW . ($ 2.50/KW for power semiconductors + $7.50/ KW )
[15] National Instruments FP-2000 series.

7. We are proceeding to test other capabilities of the DGD, including efficiency gains attributable to incremental generator engagement, and stepped variable speed through the use of multi-pole induction generators. This work is continuing under subcontract to DOE, through the WindPACT program. We will continue to assess issues such as over-current during voltage modulation and cost comparisons to other control techniques as part of this work. We expect this effort to conclude before the end of 2001.