DOE award # DEFG36-03GO13137

Abundant Renewable Energy (ARE)

Abundant Renewable Energy ARE660

Low Wind Speed Technology for Small Turbine Development

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Distribution

This report is being distributed to:

Keith Bennett at DOE Golden Field Office

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Items Not Included in this Report

The following items have not been included in this report due to their proprietary nature. Further information on these items may be available by contacting the Robert Preus at Abundant Renewable Energy, (503) 538-8298.

- Business Plan
- Controller schematics
- Controller software
- Blade aero design details
- Detailed and dimensioned drawings
- Annual energy production analysis models
- Other detailed information

1.0 Project Overview and History

1.1 Project Summary

Project Objective

Design a wind generator that is optimized for an all electric home or small business, in a low wind speed environment. The goal is for the wind generator to produce in excess of 100 kWh per day average in a 5.35 m/s Rayleigh distribution. The Cost of Energy (COE) goal is $0.12/kWh.

Background

This project is for the design of a wind turbine that can generate most or all of the net energy required for homes and small businesses in moderately windy areas. The purpose is to expand the current market for residential wind generators by providing cost effective power in a lower wind regime than current technology has made available, as well as reduce noise and improve reliability and safety.

Robert W. Preus' experience designing and/or maintaining residential wind generators of many configurations helped identify the need for an improved experience of safety for the consumer. Current small wind products have unreliable or no method of stopping the wind generator in fault or high wind conditions. Consumers and their neighbors do not want to hear their wind generators. In addition, with current technology, only sites with unusually high wind speeds provide payback times that are acceptable for the on-grid user.

Abundant Renewable Energy's (ARE) basic original concept for the ARE660 was a combination of a stall controlled variable speed small wind generator and automatic fail safe furling for shutdown. The stall control for a small wind generator is not novel, but has not been developed for a variable speed application with a permanent magnet alternator (PMA). The fail safe furling approach for shutdown has not been used to our knowledge.

Since the fail safe furling is novel, we will explain the concept for clarity. The tail is hinged on a tilted pivot that results in gravity pulling the tail parallel to the rotor blades. In this position the rotor turns out of the wind (furls) and the wind generator is safely shut down. To operate the wind generator the tail is pulled into a position perpendicular to the rotor and the rotor is forced into the wind. The tail is held in the run position by a mechanism that requires control power. Loss of control power results in the tail falling into the furled position.

This approach provides a failsafe aerodynamic shutdown method which is combined with an electric brake. Thus, there are two independent methods for controlled shutdown. This meets the IEC standards and assures that the wind generator will always be under control and appear under control.

Additional developments proposed included: increased swept area in proportion to the rating, for better low wind performance, and use of a pulse width modulated (PWM) diversion load to provide over speed control during gusting conditions so that the larger rotor does not overpower the inverter. Previous use of stall regulation on small wind generators was in conjunction with induction generators. An induction generator has a large short term over power capability, which the available inverters lack.

The project of developing this concept to the stage of a preliminary design was undertaken by a consortium including Abundant Renewable Energy (ARE) and a group of consultants. ARE was to provide project management, manufacturing planning, structural analysis and mechanical design. GEC was to provide FAST modeling and project review. Outback Power planned to provide their existing inverter platform and work collaboratively with Abundance Technologies to adapt it to the high voltage input and power tracking required for the ARE660. Foam Matrix was to provide their existing blade design and structural analysis that had been developed under a DOE grant administered through Scandia. G2 was to provide alternator design and optimization studies. MG Enterprises (Helen Hull) was to provide market research, financial management and business plan development.

1.2 Kick off Meeting

On December 9th 2003 we held a Kickoff Meeting at the National Wind Technology Center (NWTC). We reviewed the project plan and proposal from a technical prospective. We looked at a sample of the Foam Matrix blade that had been tested at the NWTC and discussed the blade from a performance and structural standpoint with the staff at the NWTC most of whom had tested the blade. While any structural short comings were deemed correctable, the appropriateness for the design for our application came into question. The primary concerns were stall characteristics, sensitivity to roughness, and noise. While other areas of the project received useful and often extensive discussion, none were severely challenged like the blade selection. The kickoff meeting discussions provided a great foundation for undertaking the next tasks of developing the design specifications and carrying out the design trade off studies. As a result of the concerns about the Foam Matrix blade design, we attended a blade design workshop at SANDIA and assigned Dayton Griffin of GEC with developing a new blade design that could be our baseline for the trade off studies.

1.3 Business Plan

Preliminary research on the Market Plan was begun through data gathered at the Global Wind Conference 2004 and 2005, as well as through meetings with dealers and distributors of renewable energy equipment. A summary draft of the Business Plan and Market Analysis was completed by July 2005 and a detailed version was completed during 4th quarter 2005. Robert Preus and Helen Hull's attendance at the NREL Industry growth conference in November 2005, contributed significantly to the drafting of the business plan. In March 2006 Robert Preus and Helen Hull attended the Oregon Clean Energy Base Summit to determine the available support for manufacturing clean energy products in Oregon and the U.S. A significant revision to the business plan was begun in the 2nd quarter of 2006. It reflected information obtained in Oregon Summit as well as refinements to the financial projections, reflecting costs and pricing updates.

The business plan is based on selling a family of wind turbines with swept areas of 110, 220, 442 and 660 square feet. We found it necessary to include the family of turbines to generate the volume of product needed to create a profitable business. In 2005, ARE unexpectedly found itself designing and manufacturing an ARE 110 and an ARE 442, when the African manufacturer, whose turbine ARE was importing and distributing, faltered due to production, exchange and quality control issues. ARE was able to quickly design and produce these machines because of the research it had already done under this grant.

In the first quarter of 2006 we refined and expanded the business plan in response to input from a few investors that we asked to review it. Adjustments were made for cost reductions as production volume increases. Capital costs for equipment were reviewed and increased.

1.4 Conceptual Design

The conceptual design process is the foundation for all of the design work to follow. We selected eleven concept evaluation tasks. Ten of the eleven concept tasks were completed. The remaining item will not impede proceeding to detail design and will be finished as time allows.

Concept 1: Turbine Configuration involved looking at three options. We compared the industry standard of a passive side furling configuration, a delayed side furl, and our proposed failsafe furling system. The failsafe furling system offered all of the advantages of the delayed furl system plus a safe shutdown at about the same cost. Both systems offer significant performance advantages over the passive side furling system. The performance advantage is that the post stall power for the delayed furling and fail safe furling configurations is better than the post furl power of the standard side furling configuration.

Concept 2: Tower Configuration involved evaluating the cost differences between truss and guyed pole towers. Within the constraints of our design criteria there is little difference in cost between the two. It appears that in this size range the choice is a matter of preference based on aesthetics, convenience of tilt up towers, and the space requirements of tilt up towers. Based on 2005 prices the 25 meter towers cost approximately $7,000 to manufacture and the 37 meter towers approximately $10,000. These costs do not include amortizing any development or equipment costs.

Concept 3: Alternator Type involved comparing the advantages of three alternator configurations; drum type (original proposal), axial, or wound. An axial PMA would be less expensive, but would be much less efficient. A wound rotor alternator would be more complex, more expensive and more difficult to use as an electric brake. We concluded that there was no justification to change from a drum type PMA.

Concept 4: 10 kW AC Output plus 5 kW of Heat Load. We started this evaluation by calculating the potential bonus energy available and found that it was 25%. This was significant enough to be very interesting. We delayed further work until we had developed the new blade design enough to have higher confidence in the available bonus energy. As we developed the blade design, a derivation of this option became the baseline approach to developing a power control approach that reached rated power in a low wind speed. More discussion on this topic will be covered in Task 4.1 below.

Concept 5: Blade Airfoil Options were reviewed, after it was determined that the Foam Matrix blade originally proposed for the project was inappropriate because the airfoil would have a hard stall, is sensitive to roughness and is fairly noisy when clean. Dayton Griffin of GEC conducted an extensive review. He used the S822 and S823 airfoil set as a baseline. He reviewed NREL, public domain, Delft and Riso airfoils. Except for the FX63-137, none had confidence of desirable performance in our Reynolds (RE) number range. The FX63-137 has good aero performance but presents structural difficulties in our size range. Blade design proceeded based on the S822 and S823 airfoils.

Concept 6: Blade Manufacturing Approaches have been reviewed. The baseline configuration is RTM blade manufacturing. Information on other manufacturing approaches has been gathered, but in this size range nothing was discovered that was appropriate and superior in cost. Most low cost production techniques have a very high tooling expense that is not suitable for our volume of production and are also best suited to open structures such as car body panels. Several potential blade manufacturers have been contacted and several manufacturing approaches were discussed.

Concept 7: Controls for Diversion Load. Richard Westlake and Dr. George Gogue evaluated the possibility of configuring the system to allow a single phase heat load to be powered by the alternator as a diversion or braking load. They looked at several ways of achieving this goal and all were found to create more problems and expense than they prevented. The advantages of using single phase loads and controls, appears to be best available by inverting the output. If we need AC for our diversion load, a simple modified square wave inverter would work effectively for a resistance load and be inexpensive.

Concept 8: We evaluated a new approach for Alternator Bearing Configuration. That configuration uses a single slew ring bearing at the outside diameter of the alternator. The potential advantage is the elimination of substantial casting and machining detail in the alternator. A study of available bearings revealed that in addition to the price penalty on the slew ring bearing there were other problems. The slew ring bearing operating at alternator rpm has seal life and grease interval problems, as well as seal drag of 20 to 40 foot pounds. Since maximizing maintenance interval and low wind energy production are both design goals, this approach was determined to be unacceptable.

Concept 9: Nacelle & Tail Configuration for Aesthetics will be investigated for cost and appeal. We have a preliminary appearance designed. Further work has been deferred until we have a better developed idea of the space requirements for the furling equipment and tail structural hardware. We worked with an artistic design consultant, Michael Holligan, to develop a tail and tail logo design. This process will be completed during detail design.

Concept 10: Was an Optimal Rating and Diameter Study. The development of the blade baseline design affected this study. We found that to achieve our low wind performance goals, we had to use a 9.5 meter diameter rotor. We also found that limiting power, while maintaining performance below rated power; we need to develop a control strategy that was an extension of Concept 4.

Concept 11: Tail Furling System Actuator Approach was considered. We found that electromechanical actuators were available that would be directly replaceable with either pneumatic or hydraulic actuators. In other words, we did not need to choose one approach since we could offer several options or change which approach was used with little impact on the rest of the system. For instance, we may sell machines with pneumatic actuators in warm climates and electro mechanic actuators in cold climates.

1.5 Preliminary Design

Task 4.1: Blades: The blade aero design is completed. There will be some refinement of the details as the fairing of the blade is finalized, especially in the blade root airfoil to mounting transition. After the structural design has been determined, there may be further modification of the root transition.

We did investigate a configuration where the blade airfoil was carried clear into the alternator. In other words we eliminated the root transition. Dayton developed two versions with this approach and found that both offered small benefits in performance and starting torque. When we estimated the cost of the structure that the blades would mount to, the costs exceeded the value of the increased performance.

The blade design is based on the S822/823 airfoils with a 9.5 meter diameter. The design tip speed ratio (tsr) is 6.5, the tip pitch is 2.5 degrees, and the peak Cp is 0.47. The blade delivers good starting torque. A rendering of the blade is attached in Appendix 1.

The development of a blade that provided good performance both pre and post stall, good starting torque, and could be limited in peak power, proved a challenge. Dayton Griffin (GEC) did a great job of working with us as we explored the options and developed a control strategy to match one of his blade design options. Paul Migliore provided assistance in the development of a blade tip design.

Blade structural design work has not begun. We did an analysis of a composite I-beam that would fit into the blade root envelop and determined that was space for a structurally adequate design. Structural design will be performed during the next phase of the project. This is necessary since the original project plan was based on using an existing blade design and the project did not have significant funds allocated for blade design.

We investigated composites manufacturing approaches by reviewing current literature and meeting with composites experts and manufacturers. We concluded that early low volume production is likely to be wet lay-up composite transitioning to RTM process as volume and capital allow. We are continuing to follow developments in alternative blade construction approaches, especially those involving thermoset plastics that can be recycled.

Task 4.2: Alternator: The alternator preliminary design is complete. Dr. Gogue and Mr. Westlake performed significant analysis in maximizing the efficiency from the mechanical input of the rotor to the DC link. The software used for the alternator design and analysis assumes a resistance load and rectification increases losses in the alternator. We had to determine the losses and assure that we were providing sufficient cooling. We have evaluated several active rectification and power factor correction approaches and found none that were applicable, efficient, and cost effective. Many are only efficient in full power or constant frequency applications.

Alternator structural design and thermal analysis are complete. Many bearing options, including hub and spindle packages for agricultural machinery have been evaluated. Bearing selection is complete subject to ongoing review as the loads document is refined and updated. A conventional sealed ball bearing has been selected. It offers the best value and confidence of ongoing availability.

Structural design and analysis are well developed. Due to the configuration of the ARE660, with the alternator providing support for the blades, deflection is the critical factor in the alternator structure. There is only 1.8 mm nominal air gap in the alternator and the manufacturing tolerance will reduce the available room for deflection. The low speed shaft, bearings, and magnet drum all deflect. FEA analysis models of the shaft and drum have been developed. The models were used to predict deflection and adjust the structure to keep the deflection within acceptable limits.

Studies of cost versus heating and efficiency were conducted. A larger alternator will run cooler and has more copper, laminations, and magnet mass. It looks more expensive;

however, the magnets are by far the biggest expense and their price varies with temperature rating. In this case, better performance costs about the same.

Studies of the effects of physical manufacturing tolerance and magnet strength tolerance on alternator performance and compatibility with power electronics were performed. Nominal dimensions and tolerance for air gap were developed that are manufacturable and meet expectations for performance in the power system.

Independent of this project, ARE has just finished designing and building an 8.5 kW alternator of a similar configuration. Based on what we have learned on that project we reviewed the design details for improved manufacturability and decreased cost. Key details for manufacturability seem to be slot fill factor and winding pattern. We started with a 70% fill factor, not accounting for slot liner and this proved difficult. We used a three tooth winding pattern with short end turns and this proved difficult as well. After reviewing the design, we reduced the fill slightly and retained the three tooth winding pattern. We also developed a six phase winding pattern for the ARE442 alternator to reduce vibration from torque ripple. The torque ripple resulted from rectifying the output of our low inductance, high efficiency alternator. The six phase winding did not solve the vibration problem.

We have also performed a preliminary design that provides the slightly higher voltages required for the current design, which now uses a WindyBoy inverter. Please see Tasks 4.3 and 4.4 below.

Task 4.3: Control/Converter: The lack of availability of the inverter manufacturer team initially delayed progress and in November 2004 a significant portion of the inverter modification design was shifted over to Richard Westlake, from Abundance Technologies. In the interim, progress was made on the converter design with allowances for integration issues with the inverter to be resolved at a later date.

As a result of our difficulties in making progress with development of an inverter system with OutBack Power, we evaluated the new WindyBoy 6000 which was introduced by SMA in late 2004. This inverter has the advantages of being in production, UL listed for wind generators, and having the potential to eliminate some of the power controls requirements planned for use with OutBack inverters. See Task 4.4 below for more discussion of inverter analysis.

Investigation into radio frequency interference (RFI) requirements informed us that the requirements were very stringent and the configuration for diversion load control that we were working with would not meet those requirements. Richard Westlake’s preliminary investigation led him to believe that correcting the RFI problem would be prohibitive. Richard developed a set of other options we could pursue and we evaluated these alternate approaches. Several of the approaches provided the benefits of no RFI or use of standard 240VAC loads or both. Unfortunately, closer investigation showed that each approach had development or production cost barriers that were too high. Richard met with RFI testing experts and formulated an approach to meeting the RFI requirements with our PWM control of the diversion load. Further consultation with the RFI testing personnel is planned during final design.

Different braking and control resistors were evaluated for cost, availability and component size. Resistance values are being fine tuned in conjunction with controls modeling and design. Subsequent experience with the ARE442 and ARE110 have shown that larger than expected diversion loads are required. We have had good experience using standard water heater elements and ceramic heater elements. Edge wound resistors proved to be noisy and unacceptable with PWM frequencies in the audible range.

A slip ring assembly was designed. Quotes from slip ring vendors indicate that it will be less expensive to purchase slip rings than it would be to manufacture our design. We have utilized the purchased slip rings on the ARE442 and they have been very satisfactory.

A lightning protection approach was developed for the power and controls systems. An analysis of component requirements was performed. We have made the lightning protection system developed here available for use on the ARE442 and 110.

Controls design is complete. It is a modular design that can be used for several models of wind generator. We have incorporated the best practices that are available for RFI suppression. We expect that to work, but will not know for sure until components are built and tested. If problems are found then, additional filtering or other design changes will be incorporated to eliminate the problem.

Board layout and software development are sufficiently complete for preliminary design. We have used some of the modular design developed for the ARE660 on the ARE442 and ARE110. We found that the modular approach creates too much assembly labor. We are transitioning to a more integrated approach, especially for the ARE110, where keeping controls cost proportionate to the rating is a big challenge.

Task 4.4: Inverter: A meeting was held on November 2, 2004 at Outback Power in Arlington, WA to begin this work. The distribution of responsibilities was shifted to allow Richard Westlake to perform some of the inverter design modification work, which OutBack Power was too busy to perform. OutBack assigned Greg Thomas as the liaison to Richard for coordinating the work and communications. Richard received an inverter that was not functional for mechanical interface information and was told to expect a working inverter soon. The working inverter would allow him to better understand the communications requirements the parts of the inverter that will remain unchanged from current production inverters. We have never received the working inverter promised from OutBack. Attempts to obtain the information from Outback Power on internal communications for their inverter resulted in denial of access to that information. It became apparent that what they expected to provide and our intended approach were not compatible.

We investigated the newly available SMA WindyBoy 6000 inverter. While their power control approach was a linear or first order fit to the wind generator performance, the losses in that approach turned out to be less than expected. We analyzed using two inverters with different settings and were able to select control parameters that gave good results. Then we approached SMA about increasing the number of linear, voltage to power parameter segments from one to several. They implemented an increase to two segments with independent slopes to meet our request. We are analyzing the additional control flexibility to determine the best settings and the consequent performance compared to ideal. It appears that we can get within a few percent of ideal in annual energy for the design wind speed distribution. The losses are higher in lower wind speed distributions.

When ARE started this project, inverter costs were very high. However, in the last few years, inverter costs have come down. In August 2005, independent of this project, ARE designed and manufactured a turbine with a 7.2 meter blade to fulfill a commitment the African Wind Power manufacturer could not meet. The turbine design was so successful, that ARE was able to increase the peak power rating from 7.5kW to an 8.5kW rating. In December 2005, ARE successfully upgraded the SMA inverters in this machine to two SMA Windy Boy 6000's and the peak power rating was increased to 10kW. Because of ARE's success with its 7.2 meter machine, which is in commercial production, and the trend toward declining inverter costs, ARE has decided that it is no longer necessary to limit the peak power on the ARE660 to 10kW to control inverter costs. Accordingly, ARE anticipates the ARE660 peak power rating to increase from 10kW to approximately 15kW.

Task 4.5: Tail Assembly: Modeling of furling behavior with different tail fin sizes and boom lengths delayed work on the tail assembly. We had to work with configurations that included offsetting the rotor from the yaw axis to get the size of the tail fin and tail boom down to an acceptable level. With the sizing of the tail boom and fin complete, we have a preliminary tail assembly design. Approaches for mounting to the main frame, actuator linkage, and other aspects have been developed.

Task 4.6: Mainframe: We have an approach that we like for fabricating a main frame. Since the work on the mainframe design was delayed due to the challenges in the furling system design, we did not complete an extensive structural analysis of the mainframe design. That task will have to be completed during the next phase of the development of the ARE660.

Investigation of different nacelle cover approaches with a focus on materials and fabrication techniques was preliminary. Further nacelle cover design will be conducted during the detail design phase of the project.

Task 4.7: Yaw bearing: The yaw bearing has been selected. A final review of the yaw bearing selected will be conducted during final design.

Task 4.8: Tower: Tower design work is based on a three leg angle steel truss tower approach and a tilt up guyed tower approach. New structural code requirements have been adapted and as a result ARE had to review all tower design analysis. The new code calls for ice loading combined with wind loading. There are also local terrain wind acceleration factors which make each site design review unique. We are considering whether to design to the maximum terrain acceleration factor or some smaller factor to cover most sites. The maximum combination of factors results in a wind force of three times standard. We have conducted design review of several similar towers for customers using the new requirements and found that the ice loading is workable in most locations.

Our experience with the expense of using a crane for service of non tilt down towers has prompted us to develop a built in service crane for these towers. We have fitted our ARE442 wind generator with such a device and it has worked well.

Task 4.9: Dynamic Analysis: Dr. Malcolm, Global Energy Concepts, has a running FAST model and has produced a preliminary set of loads. He has developed tail requirements for satisfactory furling performance. Dr. Malcolm refined the 50 year extreme gust modeling. Initial results showed very high loads for the 50 year extreme gust. Detailed review of the modeling results showed that the rotor furling was exceeding 90 degrees off of the wind and causing large tower oscillations. The real ARE660 will be constrained to prevent over furling, so the model has been modified and results are much better. We have found fairly high loads in the extreme gust scenario if the rotor is allowed to rotate. Model predictions of the rate of rotation are highly unreliable, since the aero routines are not designed for highly skewed flow. However, it is probably accurate that maintaining the rotor in a stopped condition will reduce extreme wind loads. We are altering the control design to allow the unpowered state to provide braking for the rotor. In order to maximize the reliability of the electric brake system, it will be installed in the nacelle. This will eliminate many potential failure points, including the slip rings. The preliminary loads table is complete. Further work is planned during the detail design phase of the project.

1.6 Benefits from this Program

ARE was importing a small (3.6 meter diameter) wind generator (the AWP3.6) at the time that the grant was awarded. We continued to develop that business and the business of manufacturing towers for the imported turbines during early stages of this grant. In December of 2004 we were informed by our turbine supplier that he would not be able to deliver the new AWP7.2 that we had promised to our customers. We had developed the alternator design for AWP and with the knowledge and experience developed under the grant we decided to proceed with the remainder of the design and honor our commitment to deliver a 7.2 meter machine. This wind generator is the ARE442 (442 square feet of swept area and rated at 10 kW). We also made a decision to design and produce a replacement for the AWP3.6 which is called the ARE110 (110 square feet of swept area and rated at 2.5 kW). For both wind generator models the alternator, blade and many other design features benefited from our experience with the ARE660 design work. Without the ARE660 experience, developing the ARE442 and the ARE110 would have been too big a task for us to undertake.

ARE110 wind generator in Newberg, OR

ARE442 turbine on Martha’s Vineyard, MA

ARE442 installation – Martha's Vineyard, MA

2.0 Power and Control Systems

2.1 System description

The power and control systems consist of a voltage clamp/controller (VC), electric brake, diversion load, furling actuator system, and two inverters. The control system manages startup and operation to keep the ARE660 operating within the design parameters. This includes testing of control functions on startup and maintaining the rpm range in all wind conditions. The Windy Boy inverters load the wind generator correctly to keep the rotor operating near the optimum rpm in low to medium winds. The VC limits rpm in high winds. Since this is a stall regulated wind generator, the load must always be sufficient to limit rotor rpm for power control. The VC uses the diversion load to augment the inverters which have no surge capacity over their 6 kW each rating.

2.2 Voltage Clamp/Controller

The voltage clamp converts the variable voltage and variable frequency, three phase AC from the alternator to DC for the inverters. It also provides overvoltage protection for the inverters and over speed protection for the wind generator. The VC was designed in a modular configuration so that the same boards could be used for several sizes of wind generator. While there is only one control board for any VC, there are two rectifier boards and two PWM boards for the ARE660. This allows the use of inexpensive components and a single board for each function for smaller machines and multiple for larger machines. We have gone on to implement this design for the ARE442 and ARE110 VC. While it has worked well functionally the expected cost saving were not realized. The cost of assembling the VCs is high and far exceeds any savings from using the same boards for several models. Careful design for rapid assembly could improve the situation and integration of the rectifier and PWM boards would help as well. Still the lesson here is that assembly costs are more significant in low volume production of power electronics than component costs. Schematics for the VC and the boards in the VC are in not included to protect proprietary information. Copies may be provided for review. A picture of the ARE442 controller is attached as Appendix 2.

The VC as designed has a proprietary controller board that controls all of the functions. It has isolated inputs for diversion load thermal sensor, DC link voltage, rpm on each phase, DC link current total and to the inverters, and serial port for programming the microprocessor. It has an isolated output to control the brake contactor and tail furling actuator. During startup it tests the furling, brake and diversion load functions. The control logic plan is not included to protect proprietary information. Copies may be provided for review.

The rectifier boards convert the alternator output to DC, measure current to the inverters and overall, detect rpm on each phase and output signals to the control board. The DC output is supplied to the inverters and the PWM boards. The Schematic is not included to protect proprietary information. Copies may be provided for review.

The PWM boards provide current to the diversion load to control the voltage and rpm of the alternator. The control board determines the required duty cycle and sends a signal to the PWM board. The voltage sensing circuit is on this board. The Schematic is not included to protect proprietary information. Copies may be provided for review.

2.3 Diversion Load

The diversion load is located near the controller and is used by the VC to control the voltage and protect the inverters. The load at the diversion load heaters is a function of the PWM duty cycle and the DC link voltage. The diversion load enclosures are fitted with thermal sensors that open if the temperature exceeds 60 degrees C. If a thermal sensor trips the VC applies full diversion load and releases the brake contactors. The turbine stops in approximately five seconds. The turbine remains stopped until the thermal sensor closes and goes through an additional five minute wait.

2.4 Brake System

The electric brake and furling actuator are located in the yaw head. The brake is connected to the alternator with a normally closed contactor. If control power is lost for any reason the contactors close and the brake load is applied directly to the alternator. The furling actuator (if pneumatic or hydraulic) is held in the run position with a normally open valve. Loss of control power results in the valve opening and releasing the tail which allows gravity to move the tail to the furled position.

2.5 Inverters

The inverters are 6 kW rated and are manufactured by SMA. They begin producing power at 250 VDC and produce power at a level that is determined by the DC voltage and the software settings. We can program the inverters maximum power level and the voltage where this occurs. We can set a midpoint voltage and the power level at this voltage. This approximates the desired power curve with two line segments. The surprising thing is that on paper this only results in a 2 or 3% loss from an ideal curve. A Sunny Boy manual may be obtained for review. There is currently no Windy Boy manual available due to the low volume of Windy Boy sales.

3.0 Components

3.1 Permanent Magnet Alternator (PMA)

The alternator rotor consists of the rotor casting and magnets attached to the inside diameter of the rotor casting. Ductile cast iron is the specified material for the alternator rotor. This material provides a high level of strength and durability. Casting the shape is an economical way to create the part versus a weldment or bolted construction. A casting also allows for the easy integration of vent ports for cooling the alternator. The rotor's main functions are to give a location for the blades and the magnets to mount.

The alternator uses Neodymium Iron Boron (NdFeB) material for the magnets. They are bonded to the inside diameter of the rotor casting with an adhesive. The magnets have an arc shape that matches the inside diameter of the rotor for a consistent bond line. Each pole consists of two (2) magnets end to end. This is due to the size requirements for manufacturing magnet material. The poles are longer than common manufacturing processes allow so using two (2) magnets end to end is a solution to the length requirements. This does require a long working life adhesive and fixture tools in order to install all the magnets and then compress the two (2) magnets at each pole together while the adhesive cures.

The Support Plate & Axle Weldment serves the function of supporting the alternator stator and the alternator rotor, to which the blades are directly attached. The Support Plate & Axle Weldment is also the interface between the mainframe and the alternator assembly. The Support Plate & Axle Weldment is constructed of two (2) key parts. The first part is the Support Plate for Axle and Stator. This plate is machined to provide holes for mounting the stator and a location for the Alternator Axle. The Alternator Axle has an interference fit with the Support Plate and is then welded on one side to create a cantilevered beam. The Axle will support two (2) sealed deep groove ball bearings for the Alternator Rotor Casting.

The stator assembly consists of lamination steel that is stacked together to make the stator core assembly which is bolted together. Bolting is preferred versus welding. Bolting provides a stronger joint and can provide a dimensionally accurate mounting pattern. The copper alternator windings are coiled around the teeth the stator core assembly and then the entire stator is varnish dipped and backed to seal the assembly and fill the voids between wires to reduce the possibility of damage due to vibration. The entire stator assembly is bolted to the Support Plate & Axle Weldment resulting in a stiff and secure assembly.

Structural analysis for this critical component is covered in the Section 4 titled Loads and Analysis. The design driver is maintaining the air gap between the magnets and the stator. Shaft, bearing, and rotor casting all deflect and the total deflection must be less than the minimum air gap including the manufacturing tolerance.

3.2 Mainframe

The yaw head connects all of the parts together. This has the interface for the yaw bearing, alternator and tail, as well as slip rings and the tail actuating device. The design can be constructed from plate steel that is cut to shape with a CNC laser and then formed as necessary to obtain the proper shape. Multiple parts can be welded together. It would also be possible to create a casting design that would accomplish what the weldment does.

The yaw head also houses the tail actuation system. This system consists of a pneumatic cylinder (hydraulic or electro-mechanical options would also work) used in conjunction with a lever to pull the tail into the run position out of the furl position. The pneumatic cylinder requires the use of a small reservoir and a pneumatic pump which are also contained within the yaw head.

A small amount of electronics is contained within the yaw head. The largest components are the brake resistors. A voltage monitoring circuit is used to act as an over voltage shut down. Electromagnetic relays are used to engage the brake resistors as required by the controls.

The design of the yaw head calls for the alternator shaft to be offset from the vertical axis of the yaw bearing by 0.2 m. This allows the turbine to furl about the vertical axis to a safe position. The rotor is also tilted from the vertical by 8° to allow the blades to clear the tower during operation.

3.3 Yaw Bearing

The yaw bearing is a single slewing type bearing using a quantity of 47, Ø11/16" balls. The ball path diameter is approximately 11-1/4". The bearing races are approximately 1-1/2" thick. This bearing transfers all the thrust loads and weight loads from the mainframe to the tower. Since this is a passive yaw system driven by the tail, there is no yaw drive equipment.

3.4 Slip Rings

The slip rings in the unit are used to supply electricity from the PMA to the controls and inverters. They also supply electricity from the utility grid to support the pneumatic pump and the other control hardware in the yaw head.

3.5 Tail Assembly

The tail vane has an area of 3.0m^2 (32.3ft^2). Modeling indicates that this area is sufficient to produce the desired effect of furling when required to shut down the unit. The tail vane with have a crescent moon shape made from sheet metal. The tail vane will have vertical ribs formed into it to add stiffness without increasing weight. We now use a similar design on our ARE110 and ARE442. A photo of a tail fin for the ARE442 is pictured below.

The length of the tail boom is 6.0m (19.7ft). The tail boom is made from rectangular steel tubing. This tubing is welded to a plate that has journals that interface with the pivot pin for the furling system.

The actuator for the tail can be pneumatic, hydraulic or electro mechanical with identical performance. During final design we will do the selection of which options to offer and select the appropriate components. We have researched and confirmed that there are electro-mechanical actuators that are suitable and we have done the preliminary design for a latching system for use with the actuator.

3.6 Blades

The blade aero design work was done by Dayton Griffin. First a survey of available airfoils for our Reynolds number range was performed. We selected the S822 and S823 airfoils. Once the airfoils were selected, Mr. Griffin explored a wide range of options to optimize performance in the low and medium wind speed range while limiting power in the post stall range. We were also looking for good starting torque for the blades. Explorations included designing for a peak Cp from 6.0 to 7.0 and adjusting the location of the airfoil transition area. In addition evaluation of root configurations was performed. We evaluated bringing the blade airfoil all of the way into the hub instead of creating a transition to a rectangular root. This approach was evaluated both with and without adding additional twist to the blade. While this approach showed some promise for improved starting torque, the increase in cost for building a hub to attach the blades to the alternator was not justified by the small improvement in starting torque.

3.7 Tower

Tower preliminary design work was performed on a free standing lattice tower. The design was based on a 60 degree angle configuration. The main advantage of this configuration is that no structural welding is required. We produced preliminary drawings and obtained quotes for this tower. We also did preliminary drawings and obtained quotes for an eight sided, tapered, guyed tower. We found that in this size range the costs were comparable. Both options were within the expected cost range. An assembly drawing of the top section of the lattice tower is attached in Appendix 3.

ARE Tail Fin with Logo

4.0 Loads and Analysis

4.1 Loads

A load case table was prepared by Dr. David Malcolm based on IEC 61400-2 draft. Values for the loads were derived by creating a FAST model and running each of the load cases. In order to create a model it was first necessary for Dayton Griffin to create a blade aero design and for us to develop an estimated weight based on similar sized blades. Dr. George Gogue developed a preliminary alternator design and we developed an estimated weight for the alternator. Since the alternator is the heaviest component, its weight was critical. Dr. Malcolm ran a series of cases to determine the required tail size and boom length necessary to provide effective furling under a variety of situations. In this turbine the tail is used to force furling for shut down. The initial results showed a requirement for a very large tail with a long boom. We tried using a small rotor offset and were able to reduce the tail size and boom length to acceptable levels.

A Table of load cases is presented below. Notes and references follow. The Table below dated November 1, 2004 shows early loads results. Note the very high (22 kNm) root flap bending load for the 50 year extreme wind case. The rotor was furled to 80 off yaw. Further investigation showed that this load resulted from the combination of wind speed and blade speed when the blade is vertical combining with a near optimal angle of attach. We clarified that the rotor would be prevented from rotating in high winds and the results were dramatically improved. The table dated November 1, 2004 shows the root flap bending is 11 kNm or half of the load in the previous example. The table marked November 18, 2004 consolidates the results for various configurations and load cases.

The modeling of the ARE660 showed to the extent possible with modeling that the concept of failsafe furling for shut down is feasible. Since the behavior of the model in highly skewed flow is critical and the model is not designed for such conditions, uncertainty remains. The only current approach that could remove uncertainty is field testing of a prototype.

Table of load cases to be considered

August 30, 2004

IEC load case	Load case name	Description, wind speed	conditions	Load type	Load factor	comments
1.1.1	04, 08, 12, 16, 20ms1..6	NTM Vin<Vh<Vout	Normal operation	fatigue	1.0	600 x 3 secs of simulation
1.1.2	04, 08, 12, 16, 20ms1..6	NTM Vin<Vh<Vout	Normal operation	extreme	1.35	600 x 3 secs of simulation
1.2	ECDP ECDN	Extreme coherent gust with direction change	Initial Vh = Vd	extreme	1.35	50 sec simulations
1.3	EOG508 EOG5012 EOG5020	Extreme 50-year operating gust	Vh = 8, 12, 20 m/s	extreme	1.35	150sec simulations
1.4	EDC508 EDC5012 ECD5020	Extreme 50-year direction change	Vh = 8, 12, 20 m/s	extreme	1.35	50 sec simulations
1.5	ECG	Extreme coherent gust	Vh = Vd	extreme	1.35	50 sec simulations
2.1	FRL8 FRL12 FRL20	Control system fault leading to furl	Vh = 8, 12, 20 m/s	Extreme	1.35	50 sec simulations
2.2	OffYawP12 OffYawN12	Permanent yaw error of ±30 deg	Vh = Vd	fatigue	1.0	3 x 600 sec at each wind speed. Total of 100 hrs/yr
2.3	FRLeog8 FRLeog12 FRLeog20	Loss of load with 1-year gust	Vh = 8, 12, 20 m/s	extreme	1.35	50 sec simulations
3.1	StopIn StopD StopOut	Normal electrical braking	Vh = 4, 12, 20 m/s	fatigue	1.0	50 sec simulation. 1000 occurrences of each per year
3.2	StopEOG	Normal electrical braking with 1-yr gust	Vh = 12, 20 m/s	extreme	1.35	50 sec simulation
4.1	FRLstop	Combined furling and electrical braking	Vh = 12, 20 m/s	extreme	1.35	50 sec simulation
5.1	EWM50	50-year extreme wind on stationary, furled rotor	Vh(3 sec gust) = 59.5 m/s	extreme	1.35	3 x 600 sec turbulence, Vmean = 47 m/s
5.2	EWMfat	Buffeting of furled rotor	Vmean = 42 m/s	fatigue	1.0	3 x 600 sec turbulence. 100 hrs/yr
6.1	EWM01	1-year extreme wind on unfurled , stationary rotor	Vh (3 sec gust) = 45 m/s	extreme	1.35	3 x 600 sec turbulence
7.1		Transportation, assembly, maintenance	Vh = Vd	extreme	1.5	

Notes

NTM	Normal Turbulent Model. A Kaimal spectrum will been used
Vin	cut-in wind speed (4 m/s)
Vout	cut-out wind speed (20 m/s)
Vh	Wind speed at hub height
Vd	Design wind speed (12 m/s)
P / N	Positive or Negative wind direction or yaw, as appropriate.
Load factor	These are in accordance with Table 7 of IEC 61400-2. In addition, material factors must be applied. For fatigue load case the minimum material factor is 1.25. For extreme loads the minimum material factor is 1.10.
Wind shear	The normal wind shear exponent is 0.2, except for extreme winds when it is reduced to 0.11

References

International Electrotechnical Commission, 61400-2, Safety of Small Wind Turbines, Draft, Jan. 2004

ARE660 Peak and Fatigue Loads

Model: ARE010

November 1, 2004

load	units	Peak value	Loads case	Fatigue equivalent	m (SN gradient)	EWM50 stationary	EWM50 rotating	comments
RootMxc1	kN m	5.58	EWM50_1		12			Blade root edgewise
RootMyc1	kN m	22.34	EWM50_2		12			flapwise
Spn1MLxb1	kN m		EOG50		12			20% span
Spn1MLyb1	kN m		EOG50		12			
Spn2MLxb1	kN m		EOG50		12			30% span
Spn2MLyb1	kN m		EOG50		12			
Spn3MLxb1	kN m		EOG50		12			40% span
Spn3MLyb1	kN m		EOG50		12			
Spn4MLxb1	kN m		EOG50		12			55% span
Spn4MLyb1	kN m		20 m/s		12			
Spn5MLxb1	kN m		20 m/s		12			80% span
Spn5MLyb1	kN m		EOG50		12			
LSShftFxa	kN	14.49	EWM50_3		4			Shaft axial
LSStipMya	kN m	22.47	EWM50_6		4			mt at hub-shaft (rotating)
LSStipMys	kN	22.84	EWM50_4					tilt mt at hub-shaft (non-rotating)
YawBrMxp	kN m	17.23	EWM50_4		4			Roll mt at yaw brg
YawBrMyp	kN m	9.61	EWM01_3		4			tilt mt at yaw brg
TwrBsMxt	kN m	718.9	EWM50_1		4			Tower base lateral
TwrBsMyt	kN m	526	EWM50_2		4			Fore-aft mt at tower base

Notes:

1. Loads considered:
    a. turbulent inflow @ 4, 8, 12, 16, 20 m/s mean values at hub height.
    b. Extreme IEC inflow conditions
2. Fatigue Equivalent loads are based on the SN gradients indicated and a 1.0 Hz rate over 20 years
3. All loads were run with free yaw and the tail boom restrained against furling.
4. rotor diameter = 9.5 m
5. rotor tilt = 8 degrees
6. Hub height = 36.0 m
7. EWM50 results were obtained using the ARE010 model with no induction calculation and a “normal” generator model.

ARE660 Peak and fatigue loads

Model: ARE010

November 15, 2004

load	units	Peak value	Loads case	Fatigue equivalent	m (SN gradient)	EWM50 stationary	EWM50 rotating	comments
RootMxc1	kN m	2.98	EWM50brk_3		12			Blade root edgewise
RootMyc1	kN m	11.2	EWM50brk_3		12			flapwise
Spn1MLxb1	kN m				12			20% span
Spn1MLyb1	kN m				12			
Spn2MLxb1	kN m				12			30% span
Spn2MLyb1	kN m				12			
Spn3MLxb1	kN m				12			40% span
Spn3MLyb1	kN m				12			
Spn4MLxb1	kN m				12			55% span
Spn4MLyb1	kN m				12			
Spn5MLxb1	kN m				12			80% span
Spn5MLyb1	kN m				12			
LSShftFxa	kN	12.1	EWM01_5		4			Shaft axial
LSStipMya	kN m	11.1	EWM50brk_3		4			mt at hub-shaft (rotating)
LSStipMys	kN	11.1	EWM50brk_3					tilt mt at hub-shaft (non-rotating)
YawBrMxp	kN m	12.5	EWM50brk_3		4			Roll mt at yaw brg
YawBrMyp	kN m	10.3	EWM01_5		4			tilt mt at yaw brg
TwrBsMxt	kN m	398	EWM50brk_3		4			Tower base lateral
TwrBsMyt	kN m	541	EWM01_5		4			Fore-aft mt at tower base

Notes:

1. Loads considered:
   a. turbulent inflow @ 4, 8, 12, 16, 20 m/s mean values at hub height.
   b. Extreme IEC inflow conditions
2. Fatigue Equivalent loads are based on the SN gradients indicated and a 1.0 Hz rate over 20 years
3. All loads were run with free yaw and the tail boom restrained against furling.
4. rotor diameter = 9.5 m
5. rotor tilt = 8 degrees
6. Hub height = 36.0 m
7. EWM50 results were obtained using the ARE010 model with no induction calculation and the shaft restrained against rotation.

load	units	EWM50 (rotating, furled)	EWM50brk (stationary, furled)	EWM01 (stationary, no furling)	EWM01 x 1.77 (stationary, no furling)	comments
RootMxc1	kN m	5.58	2.98	0.746	1.32	Blade root edgewise
RootMyc1	kN m	22.3	11.2	9.37	16.7	flapwise
Spn1MLxb1	kN m					20% span
Spn1MLyb1	kN m					
Spn2MLxb1	kN m					30% span
Spn2MLyb1	kN m					
Spn3MLxb1	kN m					40% span
Spn3MLyb1	kN m					
Spn4MLxb1	kN m					55% span
Spn4MLyb1	kN m					
Spn5MLxb1	kN m					80% span
Spn5MLyb1	kN m					
LSShftFxa	kN	14.5	7.44	12.1	21.5	Shaft axial
LSStipMya	kN m	22.5	11.1	2.78	4.94	mt at hub-shaft (rotating)
LSStipMys	kN	22.8	11.1	2.78	4.94	tilt mt at hub-shaft (non-rotating)
YawBrMxp	kN m	17.0	12.5	6.04	10.7	Roll mt at yaw brg
YawBrMyp	kN m	8.96	9.20	10.3	18.3	tilt mt at yaw brg
TwrBsMxt	kN m	719	398	181	321	Tower base lateral
TwrBsMyt	kN m	524	232	541	961	Fore-aft mt at tower base

Notes:

1. rotor diameter = 9.5 m
2. rotor tilt = 8 degrees
3. Hub height = 36.0 m
4. All results were obtained using the ARE010 model with no induction factor calculation.
5. Furling was restrained by a spring starting at a furling angle of 80 degrees.
6. The “EWM01 x 1.77” results are intended to correspond to a 50-year wind gust on a stationary and not-furled rotor.

4.2 Analysis

Blade

Analyses of the blade structural strength and blade mounting bolt requirements were conducted. Since detailed structural design of the blade was not part of the preliminary design effort Mr. Draper conducted an analysis based on a composite I-beam that would fit in the space of the blade root design envelop. The resultant structure in a unidirectional glass epoxy composite showed far higher strength than the worst load case for flapwise bending in the tables above. Even accounting for the difficulties of the transition in the root, it is clear that there is adequate room in the root as designed to build a structurally sound blade.

Blade mounting bolt analysis was conducted based on a 1.25 inch (31.8 mm) blade mounting stud. With these studs at the selected locations there is a minimum factor of safety of 10 in all loadings and stresses.

Alternator

The alternator is a critical structure since it provides the mounting point for the blades as well as performing the critical function of turning the power of the rotor into electrical power. In order to perform both functions effectively it needs to be structurally stiff enough that the rotating magnets never contact the stator. The nominal air gap between the stator and the magnets is 0.090 inch (2.3 mm) with a manufacturing tolerance of 0.025 inch (0.64 mm). Mr. Draper created an FEA model of the alternator and ran load cases for axial thrust loading on the alternator rotor, blade moment load on the alternator, moment load on the low speed shaft, and weight and full load torque combined. One of the FEA reports are attached as Appendix 4.

Tower

Analyses of the lattice tower design and the guyed pole design were performed to determine the sizes of the structural members and the guys.

5.0 Conclusions

As in all development projects, the work performed under the contract has revealed unexpected problems and opportunities. In May 2007, Abundant Renewable Energy identified several areas where additional effort would further enhance the work performed under the contract for the preliminary design of the ARE660, a three bladed upwind WTG with a novel failsafe furling approach for shutdown. These additional tasks would improve the value and depth of the reporting, allow better optimization of the design, or increase confidence areas where there is significant risk. This could be accomplished before committing to final design and full size prototype construction.

Task 1 Alternator Characterization & Noise Suppression

In the first round of analysis and design we looked only at the efficiency at rated power, the cost and the weight of the alternator configurations that we evaluated. The losses in the steel (eddy current losses) are small and we essentially ended up optimizing for low wire loss. We now understand that at low power, steel loss is proportionately larger and a much better analysis could be prepared by characterizing the alternator performance of the best candidates over the entire operating range. It would also be useful to determine if the modeling tools available can predict the torque in the extreme case of braking, so we can optimize braking loads.

Since ARE has now built some alternators of the same type as the ARE660, but of a smaller size, we now know that they produce an audible hum that some people find objectionable. We would like to do some modeling and testing using our smaller alternators to find a solution to this problem. We expect that the right value of inductors added to the generator output or the DC link may correct the problem. If not, then a power factor correction device will be needed.

Task 2 Modeling & Documentation of ARE442

NWTC is testing the ARE442 for certification to AWEA standards. Creation of modeling and documentation for certifying of the ARE442 would facilitate the later certification of the ARE660. Certification testing of the ARE442 would enhance the possibility of investor funding for the development of the ARE660 and would produce valuable input for the detail design phase of the ARE660 development project.

Task 2a Testing of ARE660 Concepts

The ARE442 prototype is constructed so that it is easy to reconfigure the rotor offset and furling configuration. We recently realized that we could replace some furling assembly pieces, add an actuator, and change the offset of the rotor to create a reduced size model of the ARE660 configuration. Some controller modifications would also be required. This approach would allow a real world test of the configuration concepts developed in the ARE660 project before incurring the cost of the final design and prototype construction of the ARE660. This proof of concept would make it easier to raise funds to bring the ARE660 to market.

Task 5 Blade Development

The original intent of our program was to use an existing blade design; however we determined that the blade design was a poor choice for our configuration. We did not have funds in the project to design a new blade. We used the funds that were available to do a first cut aero design. It would be very valuable to optimize the aero design and develop the structural design of the blade for the ARE660.

Task 6 Additional Modeling

The modeling to determine the expected loads for the ARE660 was performed early in the process based on estimated weights and dimensions. Now that we have better weights and dimensions it would be valuable to redo the model and loads table.

Summary Conclusion:

The configuration we conceived for the ARE660 appears to be a workable option that has advantages over other configurations currently in production. Building the ARE110 and ARE442 have validated some of the preliminary design work on the ARE660 and have also raised concerns about power control and consistent furling. We do not think that we have established clearly whether those advantages of the ARE660 configuration are sufficient to warrant the risk of undertaking the full development and marketing of the ARE660. The areas of uncertainty are whether furling behavior will match modeling results and whether controlling the rotor speed during dynamic stall will be effective with the control approach developed. Our experience with the ARE110 and ARE442 indicate that diversion load control requires substantial diversion loads for effectiveness and that furling behavior is very sensitive to rpm. The tasks identified above are potential low cost next steps to reduce uncertainty before committing to generating a final design, building a prototype, developing the manufacturing and bringing the ARE660 to market.

Appendix 1

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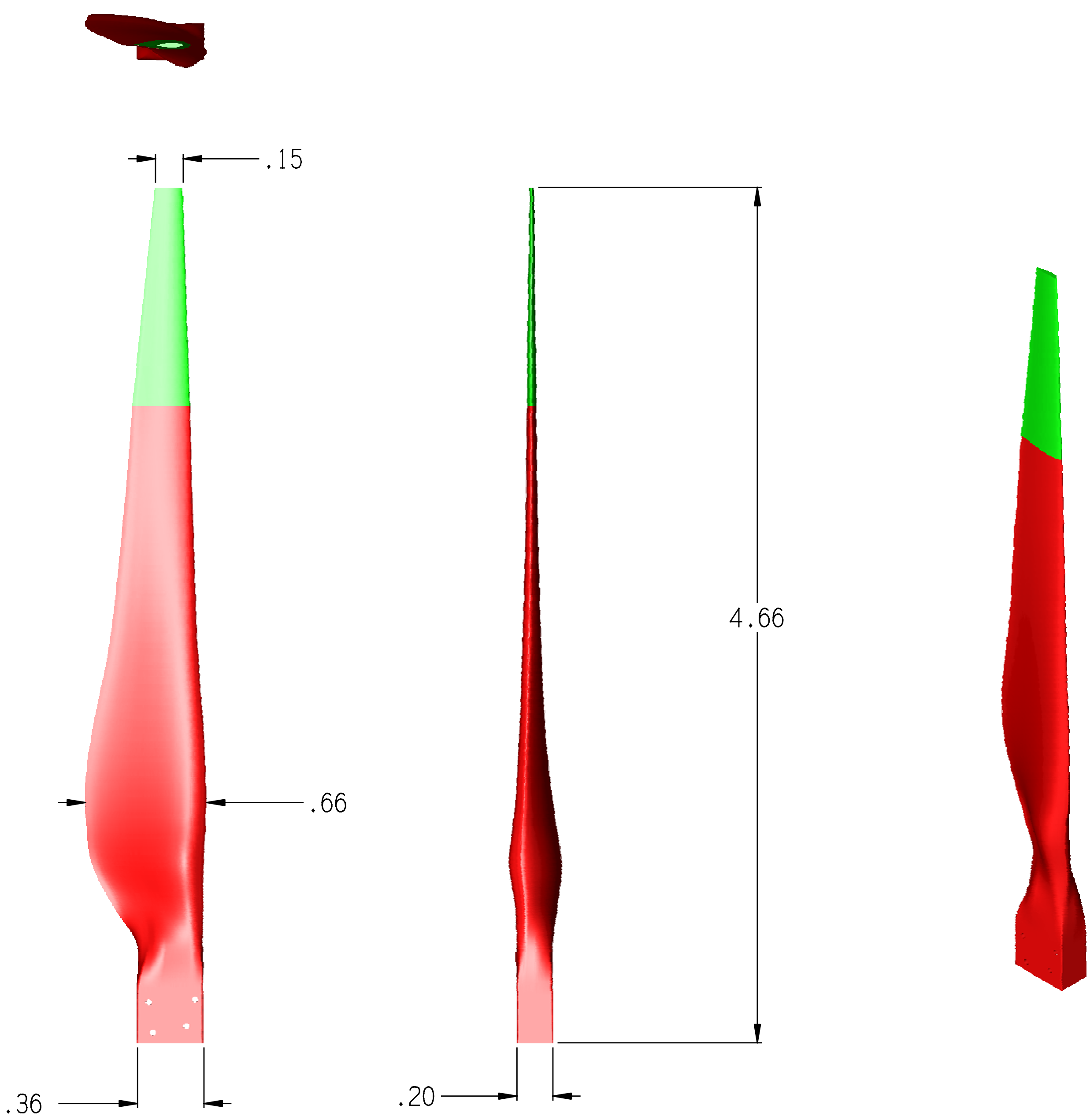

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ABUNDANT RENEWABLE ENERGY

DRAWING TITLE
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SCALE
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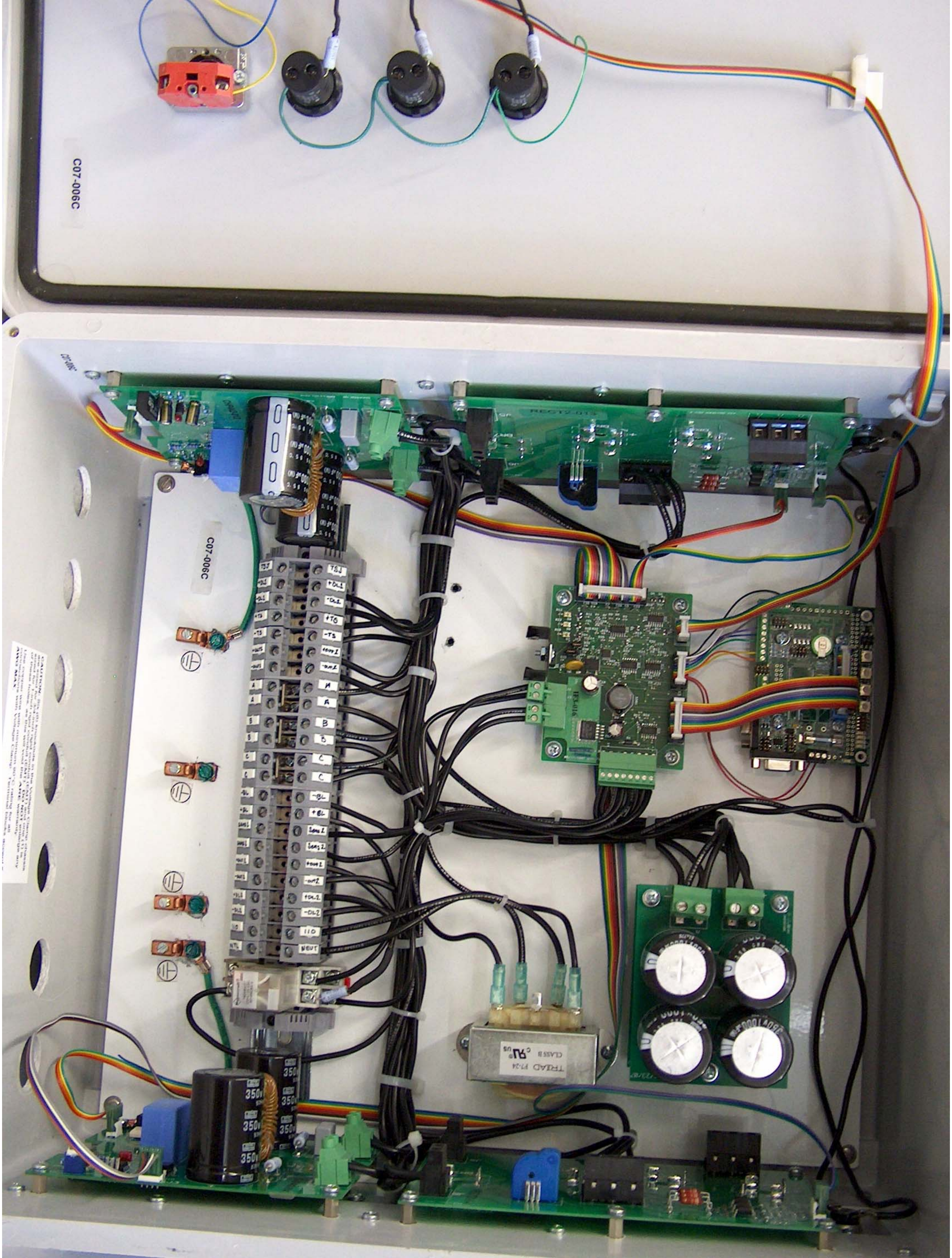
DRAWING NO. ???-?? SHEET 1 OF ? REV A

Appendix 2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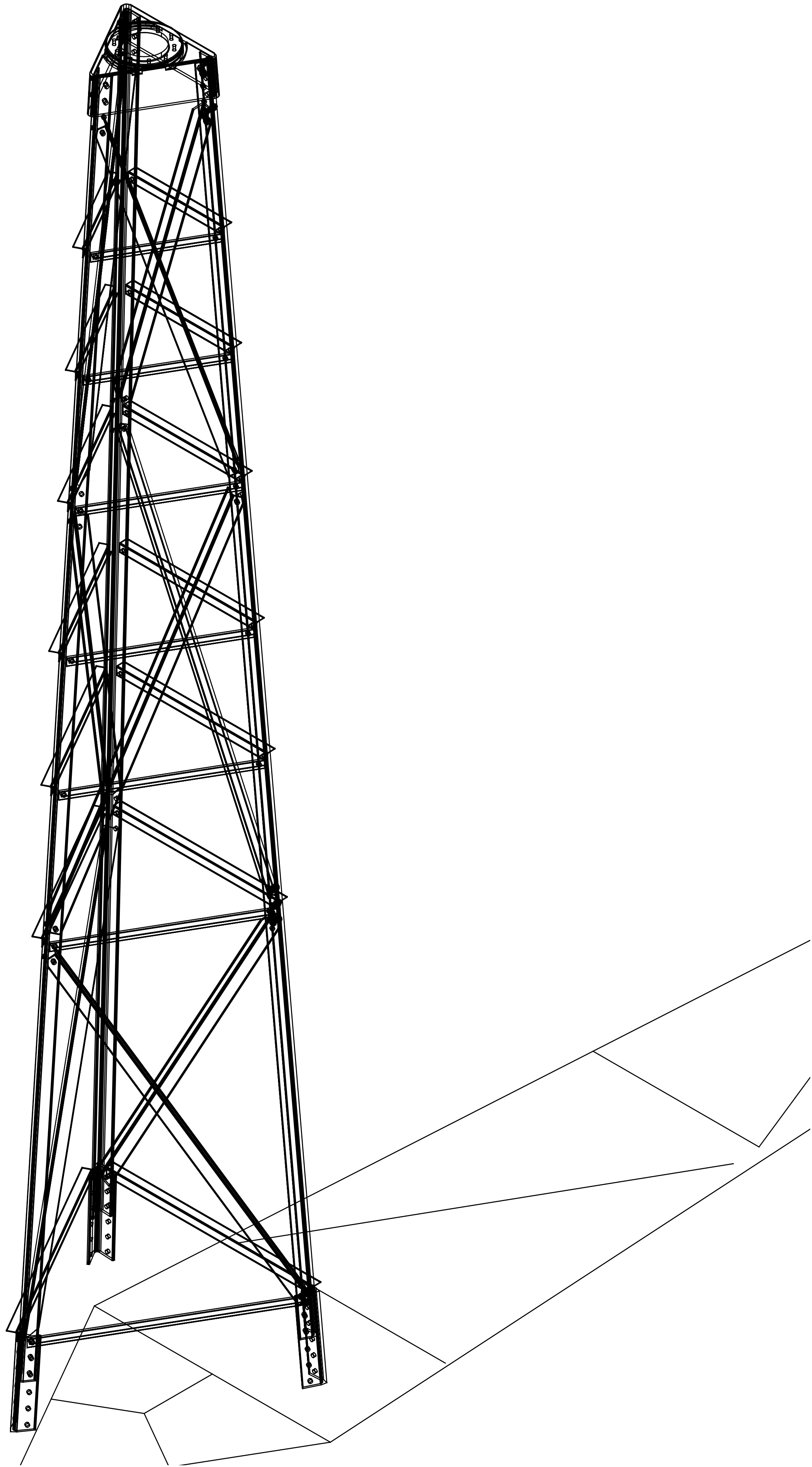
Appendix 3



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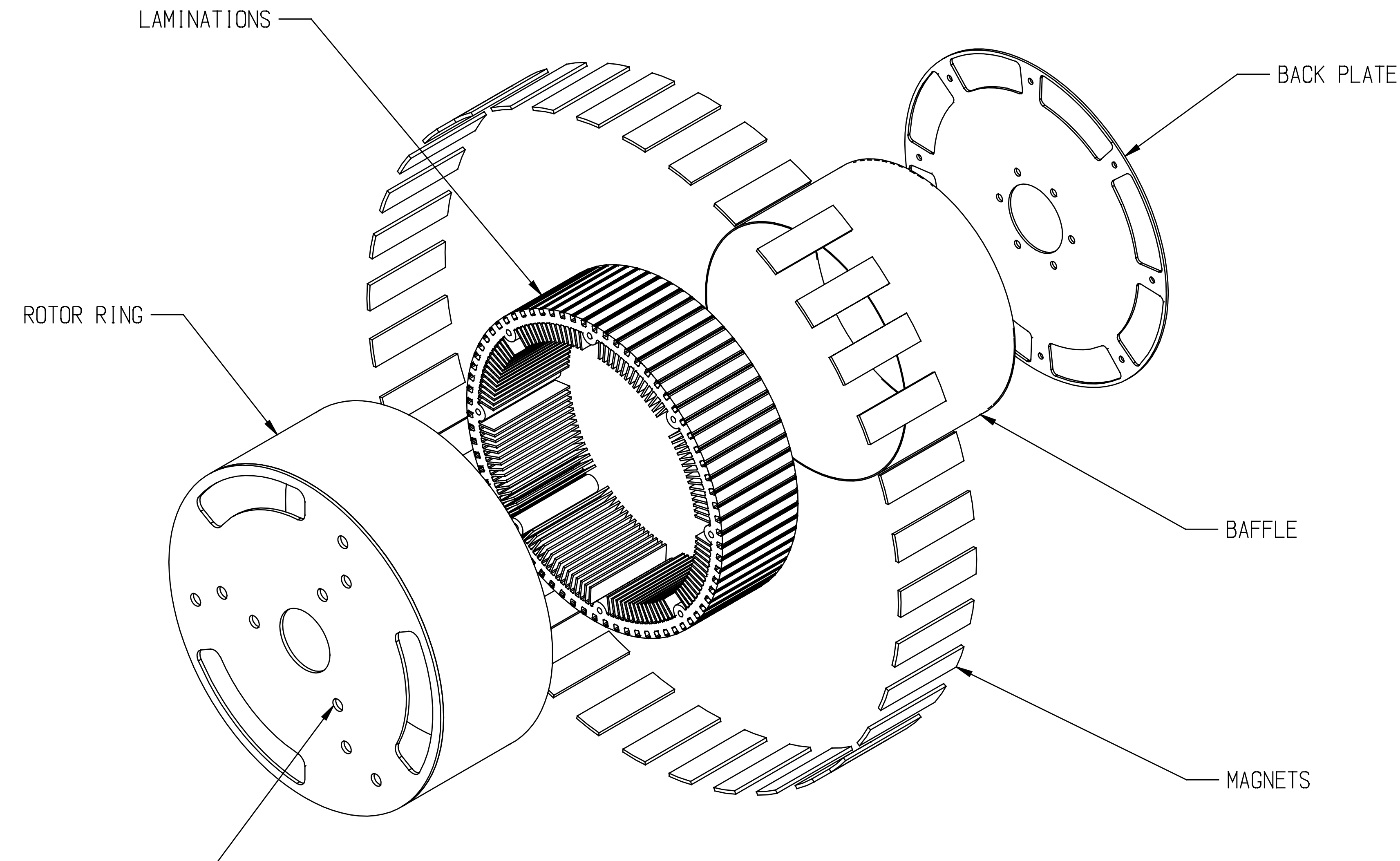

EXPLODED VIEW

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TOLERANCES:
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FRACTION ± 1/16"
.XX ± .03
.XXX ± .015
ANGULAR
± 1.0°

MODEL NUMBER:
ARE 660

MATERIAL:
????

LEGEND
REVISION ITEM NOTE

DRAWN E. DRAPER
DATE 07/23/04
CHECKED

ABUNDANT RENEWABLE ENERGY

DRAWING TITLE
ALTERNATOR ASSEMBLY

SCALE
NONE

DRAWING NO. ???-??
SHEET 2 OF 2
REV A

DRAWING NO.	???-??		REV A
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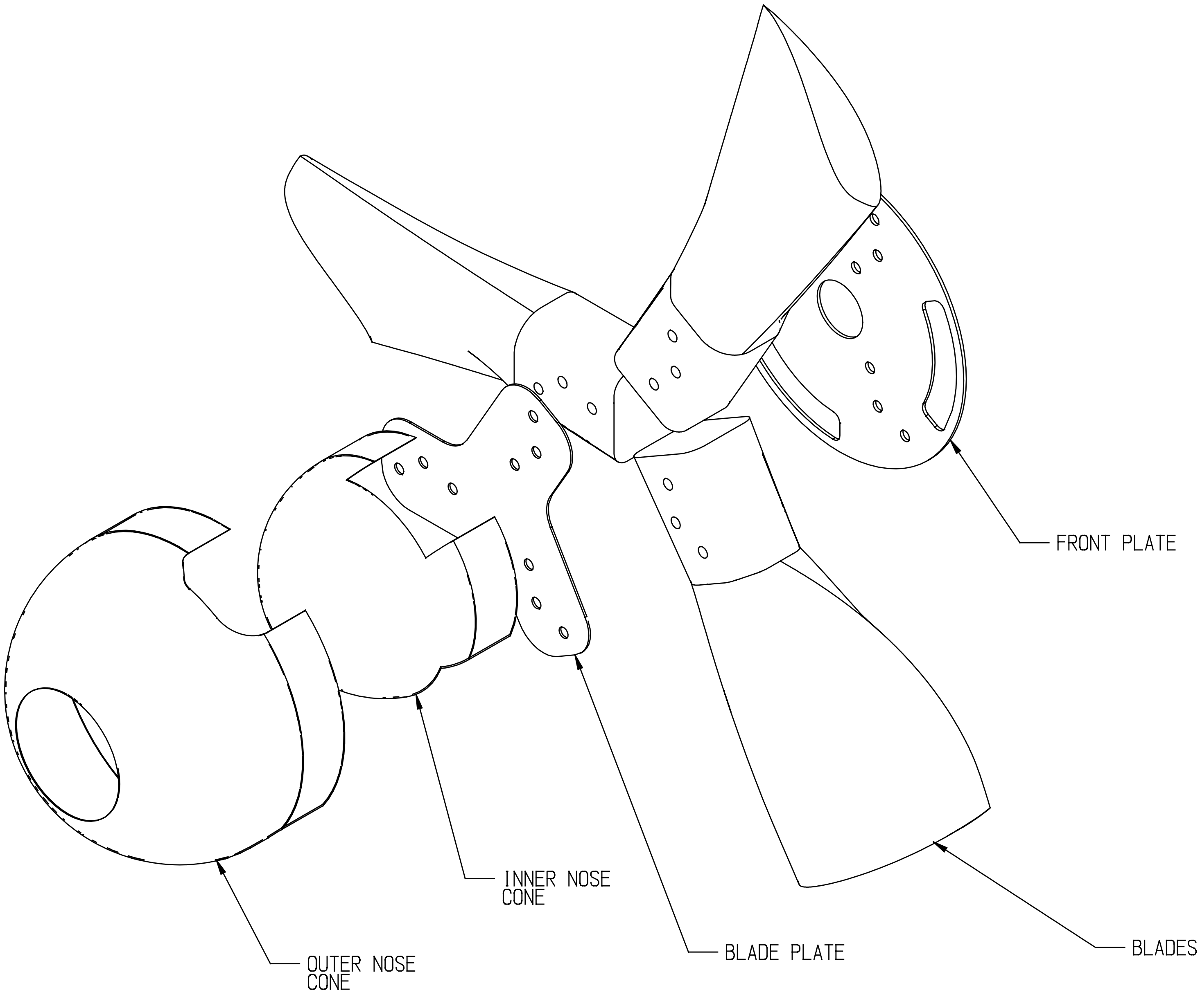

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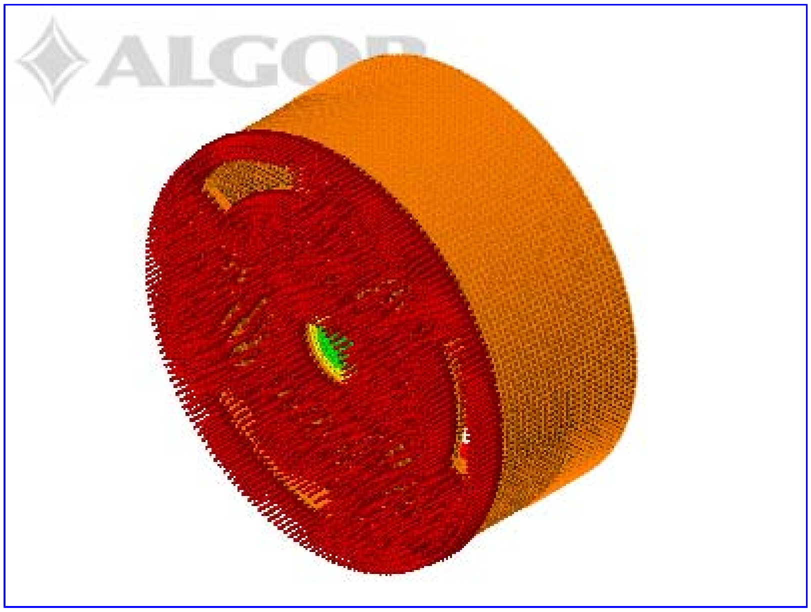
Appendix 4

Design Analysis

ARE 660



Created By

Emile Draper
Project Engineering
Project created on 11/16/2004.
Last updated on 11/24/2004.

Project checked on 11/24/2004.

Summary

Description

Analysis of the alternator mechanical design. Load Case 1 is pure thrust loading corresponding to LSStipFxa=21.5kN, EWM01 X 1.77. Gravity is acting in the -X direction.

Model Information

Analysis Type - Static Stress with Linear Material Models
Units - English (in) - (lbf, in, s, deg F, deg R, V, ohm, A, in*lbf)
Model location - R:\EMILE DRAPER\ARE660\AG hub algor test\test2\assembly 15

Analysis Parameters Information

Load Case Multipliers

Static Stress with Linear Material Models may have multiple load cases. This allows a model to be analyzed with multiple loads while solving the equations a single time. The following is a list of load case multipliers that were analyzed with this model.

Load Case	Pressure / Surface Forces	Acceleration / Gravity	Displaced Boundary	Thermal	Voltage
1	1	1	0	0	0

Gravity Information

The following lists the values used if acceleration or gravity was included in the analysis. The Acceleration / Gravity direction multiplier is multiplied by the Acceleration Due To Body Force which is then multiplied by the Acceleration / Gravity load case multiplier.

Acceleration Due To Body Force = 386.4 in / s²

Acceleration / Gravity X Multiplier	Acceleration / Gravity Y Multiplier	Acceleration / Gravity Z Multiplier
-1	0	0

Multiphysics Information

Default Nodal Temperature	0 °F
Source of Nodal Temperature	None
Time step from Heat Transfer Analysis	Last

Processor Information

Type of Solver	Automatic
Disable Calculation and Output of Strains	No
Calculate Reaction Forces	Yes
Invoke Banded Solver	Yes
Avoid Bandwidth Minimization	No
Stop After Stiffness Calculations	No
Displacement Data in Output File	No
Stress Data in Output File	No
Equation Numbers Data in Output File	No
Element Input Data in Output File	No
Nodal Input Data in Output File	No
Centrifugal Load Data in Output File	No

Part Information

Part ID	Part Name	Element Type	Material Name
1	axle	Brick	AISI 1020 Steel, cold rolled
2	support	Brick	Steel (ASTM - A36)
3	small bearing	Brick	Steel (ASTM - A36)
4	large bearing	Brick	Steel (ASTM - A36)
5	rotor	Brick	Iron, Ductile 60-41-18
6	bearing ring	Brick	Steel (ASTM - A36)
7	Part 7	Beam	Steel (ASTM - A36)

Element Properties used for:

- axle
- support
- small bearing
- large bearing
- rotor
- bearing ring

Element Type	Brick
Compatibility	Not Enforced
Integration Order	2nd Order
Stress Free Reference Temperature	0 °F

Element Properties used for:

- Part 7

Element Type	Beam
Stress Free Reference Temperature	0 °F
Layer 1 - Area	0.04908734375
Layer 1 - SA2	0.043517148714539
Layer 1 - SA3	0.043517148714539
Layer 1 - J1	3.83494873046875E-04
Layer 1 - I2	1.91747436523437E-04
Layer 1 - I3	1.91747436523437E-04
Layer 1 - S2	1.5339794921875E-03
Layer 1 - S3	1.5339794921875E-03

Material Information

AISI 1020 Steel, cold rolled - Brick

Material Model	Standard
Material Source	Algor Material Library
Material Source File	C:\Program Files\ALGOR\MatLibs\algormat.mlb
Date Last Updated	2004/07/29-15:02:00
Material Description	MatWeb
Mass Density	0.00073643 lbf*s^2/in/in³
Modulus of Elasticity	29733000 lbf/in²
Poisson's Ratio	0.29
Shear Modulus of Elasticity	11603000 lbf/in²
Thermal Coefficient of Expansion	0.0000065 1/°F

Steel (ASTM - A36) - Brick

Material Model	Standard
Material Source	Algor Material Library
Material Source File	C:\Program Files\ALGOR\MatLibs\algormat.mlb
Date Last Updated	1999/06/02-11:03:56
Material Description	Structural Steel Mechanics of Materials, 2nd Edition, F.P. Beer and E.R. Johnston, Jr. (mechanical)
Mass Density	7.35e-4 lbf*s^2/in/in³
Modulus of Elasticity	29e6 lbf/in²
Poisson's Ratio	0.29
Shear Modulus of Elasticity	11.2e6 lbf/in²
Thermal Coefficient of Expansion	6.5e-6 1/°F

Iron, Ductile 60-41-18 - Brick

Material Model	Standard
Material Source	Algor Material Library
Material Source File	C:\Program Files\ALGOR\MatLibs\algormat.mlb
Date Last Updated	2004/06/29-15:00:00
Material Description	Ductile Iron 60-40-18 "Materials Selector Issue", Machine Design, December 12, 1995
Mass Density	6.65e-4 lbf*s^2/in/in³
Modulus of Elasticity	23e6 lbf/in²
Poisson's Ratio	0.275
Shear Modulus of Elasticity	9.02e6 lbf/in²
Thermal Coefficient of Expansion	6e-6 1/°F

Steel (ASTM - A36) - Beam

Material Model	Standard

Material Source	Algor Material Library
Material Source File	C:\Program Files\ALGOR\MatLibs\algormat.mlb
Date Last Updated	1999/06/02-11:03:56
Material Description	Structural Steel Mechanics of Materials, 2nd Edition, F.P. Beer and E.R. Johnston, Jr. (mechanical)
Mass Density	7.35e-4 lbf*s^2/in/in^3
Modulus of Elasticity	29e6 lbf/in^2
Poisson's Ratio	0.29
Thermal Coefficient of Expansion	6.5e-6 1/°F

Load and Constraint Information

Loads

Load Set 1: axial force 1 yr x 1.77

Surface Forces

ID	Description	Part ID	Surface ID	Magnitude	Vx	Vy	Vz
13	LSShftFxa	5	48	4834	0	1	0

Constraints

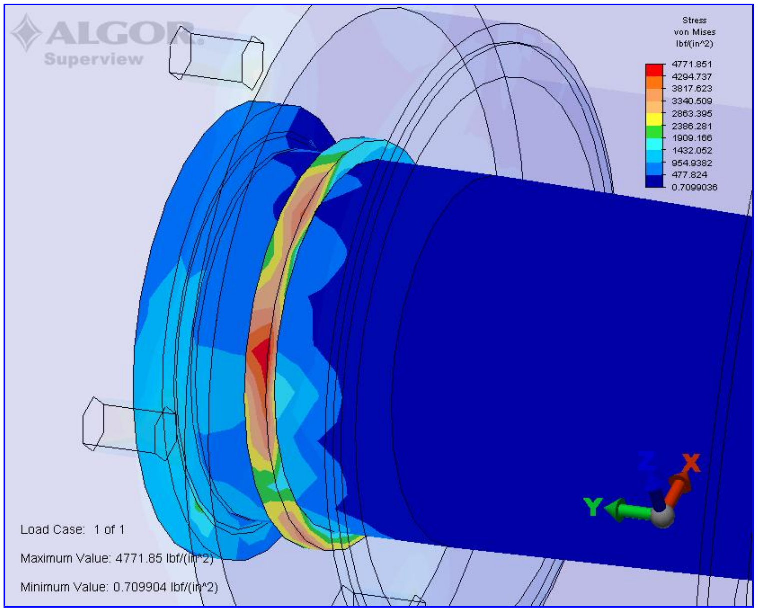
Constraint Set 1: Unnamed

Surface Boundary Conditions

ID	Description	Part ID	Surface ID	Tx	Ty	Tz	Rx	Ry	Rz
1	Unnamed	2	1	Yes	Yes	Yes	Yes	Yes	Yes
2	Unnamed	2	2	Yes	Yes	Yes	Yes	Yes	Yes
3	Unnamed	2	3	Yes	Yes	Yes	Yes	Yes	Yes
4	Unnamed	2	4	Yes	Yes	Yes	Yes	Yes	Yes
5	Unnamed	2	5	Yes	Yes	Yes	Yes	Yes	Yes
6	Unnamed	2	6	Yes	Yes	Yes	Yes	Yes	Yes
7	Unnamed	2	127	Yes	Yes	Yes	Yes	Yes	Yes
8	Unnamed	2	128	Yes	Yes	Yes	Yes	Yes	Yes
9	Unnamed	2	129	Yes	Yes	Yes	Yes	Yes	Yes
10	Unnamed	2	130	Yes	Yes	Yes	Yes	Yes	Yes
11	Unnamed	2	131	Yes	Yes	Yes	Yes	Yes	Yes
12	Unnamed	2	132	Yes	Yes	Yes	Yes	Yes	Yes

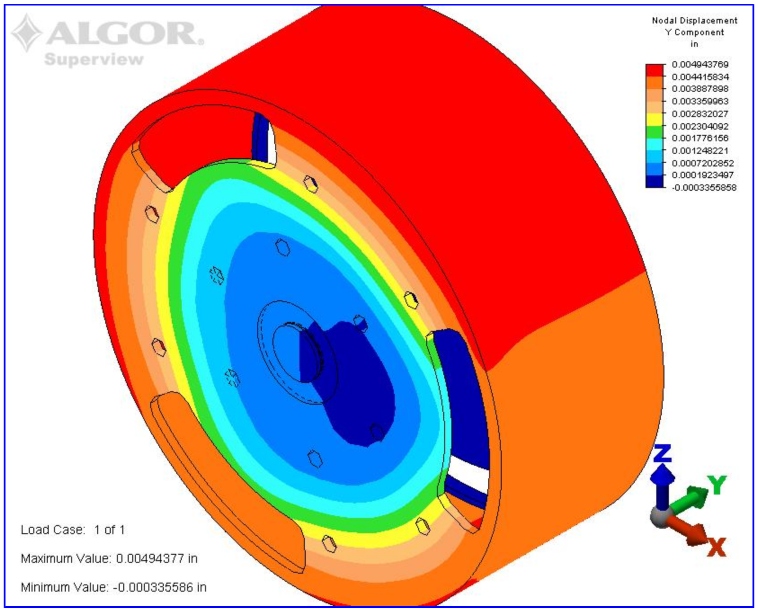
Appendix

Detail of the Axle and Ring



The axle is minimally loaded. The ring between the alternator support and the bearing reacts most of the load. This indicates that the ring is the critical element.

Displacement of Aleternator Rotor



The displacement is of small enough value to not be of concern.