The WEI6K, a 6-kW 7-m Small Wind Turbine

Final Technical Report

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ABSTRACT

This project was selected by the U.S. Department of Energy under a DOE solicitation “Low Wind Speed Technology for Small Turbine Development.” The objective of this project has been to design a new small wind turbine with improved cost, reliability and performance in grid-connected residential and small business applications, in order to achieve the overall DOE goal of cost effectiveness in Class 3 wind resources that can now be achieved in Class 5 resources.

The scope of work for this project has been to complete the preliminary design of an improved small wind turbine, including the following tasks:

- preliminary loads and strength analyses;
- analysis and design of all major components;
- systems integration and structural dynamic analysis;
- estimation of life-cycle cost of energy; and
- design documentation and review.

The project did not entail hardware fabrication or testing.

The WEI6K Turbine resulting from this project is an upwind horizontal-axis wind turbine rated at 6 kW. It features a 3-blade 7-m diameter rotor. The generator is a direct-drive permanent magnet synchronous machine generating 3-phase power at 240 VAC. The turbine is maintained oriented in to the wind via active yaw control using electromechanical servos. Power is regulated with active blade pitch control. The turbine is presently designed to be placed on a 100-foot (30m) tower.

The turbine is predicted to generate electricity at a levelized cost of energy (COE) between 7.3 and 8.9 ¢/kWh at an IEC Class II site, with an average wind speed of 8.5 m/s at hub height, depending upon whether the customer uses a guyed truss tower (the lower figure) or a monopole tower. For the NREL Reference Site, with a mean wind speed of 5.35 m/s at 10 m height, the turbine would generate at a levelized cost of energy of between 9.7 and 11.9 ¢/kWh. The lowest of these numbers is presently competitive with retail electricity rates in most of the country. The 8.9 ¢/kWh is still competitive with retail rates in many regions of the country with high electricity costs.

The study further concludes that several design changes could shave 10-14% from the cost of energy determined in the preliminary design. These changes include:

- A new tower design that offers tilt-up capability without guy wires and takes better advantage of the lowered loads produced by pitch control.
- Design a family of airfoils more appropriate for pitch regulation on a turbine of this size.
- Tune the pitch controller properly to minimize shedding of power during turbulent operation in the transition from Region 2 to 3.
- Value engineer the pitch system to shave costs, including consideration of a collective pitch system.
- Refine the design of the hub and main frame castings to minimize weight and cost.

We are generally encouraged by the results. These preliminary numbers show that we can produce a turbine that is competitive with retail electric rates at relatively windy IEC Class II sites. With further improvements in the design, we believe the turbine could be competitive at sites with lesser wind resource.

Acknowledgments

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We received significant technical advice and support from many members of the staffs at the Wind Energy Program at Sandia National Laboratories and at the National Wind Technology Center (NWTC) at the National Renewable Energy Laboratory (NREL). They are too numerous to list individually here, but we are grateful for all their help. We would like to specifically acknowledge the support we received from Ms. Trudy Forsyth, the manager of the distributed wind energy program at NWTC, and from Drs. Jim Green (NWTC) and Paul Migliore (formerly NWTC), all of whom served as Technical Monitors for this Grant and provided us substantial assistance. We also thank Marshall Buhl and Jason Jonkman, both of NWTC, for their patient assistance with the FAST software.

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1. Introduction: Background & General Description of the Turbine

This project was selected by the U.S. Department of Energy in 2003 under a DOE solicitation DE-PS36-03GO93005 “Low Wind Speed Technology for Small Turbine Development.” The objective of this project has been to design a new small wind turbine with improved cost, reliability and performance in grid-connected residential and small business applications, in order to achieve the overall DOE goal of cost effectiveness in Class 3 wind resources that can be achieved in Class 5 resources with current technology.

The project identified as a baseline a three-bladed, pitch-regulated, upwind turbine with a rated power of approximately 6 kW and a 7-m rotor diameter. Other features include a direct drive permanent magnet generator, a 30-m freestanding tower, and blades with flap-twist coupling. The originally estimated life cycle cost of energy for a mature system at the DOE Reference site (5.35 m/s annual average wind speed) was \$0.08 per kWh.

The scope of work for this project has been to complete the preliminary design of an improved small wind turbine, including the following tasks:

- preliminary loads and strength analyses;
- analysis and design of all major components;
- systems integration and structural dynamic analysis;
- estimation of life-cycle cost of energy; and
- design documentation and review.

The project did not entail hardware fabrication or testing.

The prime contractor, Wetzel Engineering, Inc., of Lawrence, Kansas, has been responsible for the project management, system integration, dynamics and performance modeling, and the design of the rotor blades. Other key team members have included

- McCleer Power, Inc., Jackson, Michigan, which has been responsible for electrical generation, power conditioning, and controls systems,
- Powertrain Engineers, Inc., of Pewaukee, Wisconsin, which has been responsible for all mechanical systems, and
- Valmont Industries, Valley, Nebraska, which assisted with the early phase of tower and foundation design.

The cost of this project was shared between the U.S.D.O.E. and Wetzel Engineering, as per the requirements of the solicitation. The Government supported approximately two-thirds of the expenses, while Wetzel Engineering and its partners incurred one-third of the project cost.

The WEI6K Turbine resulting from this project is an upwind horizontal-axis wind turbine rated at 6 kW. It features a 3-blade 7-m diameter rotor. The generator is a direct-drive permanent magnet synchronous machine generating 3-phase power at 240 VAC. The turbine is maintained oriented in to the wind via active yaw control using electromechanical servos. The turbine is presently designed to be placed on a 100-foot (30 m) free-standing monopole tower. Figure 1 shows several outside and cut-away views of the tower top hardware. Table 1 provides a general description of the wind turbine and its design operating environment. A comparison is shown of the design objectives at the project start and the predicted performance for the configuration at the time of the Preliminary Design Review conducted at the completion of the project.

Figure 1. Outside and Cut-Away Views of the WEI6K Turbine

Table 1. General Configuration of the WEI6K Wind Turbine

	PDR	Kick-Off
General Configuration		
Rated Electrical Power (kW)	6	6
Rotation Axis	Horizontal	Horizontal
Rotor Diameter (m)	7	7
Number of Blades	3	3
Orientation	Upwind	Upwind
Power Regulation above Rated	Active Pitch to Feather	Active Pitch
Yaw Regulation	Active Yaw	Active Yaw
Speed Regulation	Fixed-Speed	Fixed-Speed
Generator Type	PM Synchronous	PM Synchronous
Hub Type	Rigid	Rigid
Hub Height (m)	30	30
Design Operating Environment & Performance		
IEC 61400-1 Wind Class	II-A	II-A
Rated Wind Speed (m/s)	9	9
Cut-in Wind Speed (m/s)	4.1	3.5
Cut-out Wind Speed (m/s)	25	25
Extreme Wind Speed (m/s)	60	60
Design Life (yrs)	20	20
Net Annual Energy Production		
NREL Reference Site (kWh)	21433	23755
IEC Class II-A Site (kWh)	28517	29373

Figure 2 shows the predicted steady state and turbulent power curves for the wind turbine, along with the estimated gross annual energy production. The turbine has been designed and analyzed according to IEC 61400-1, Edition 3, Class II-A conditions, with a mean wind speed of 8.5 m/s; but using the Edition 2 turbulence intensity of 18% in all turbulent simulations, as well as at the NREL Reference Wind Site, with a mean annual wind speed of 5.35 m/s at a height of 10 m. The turbine has a cut-in wind speed of approximately 4 m/s in turbulent conditions, and is designed to cut out at 25 m/s (60 mph). The turbine is designed to withstand the 50-year Extreme Wind prescribed by IEC, which is 60 m/s for Class II. Power regulation above rated is achieved through active blade pitch control. Pitch control is effected with electromechanical servos. Each of the three blades has its own pitch drive and controller. Below rated, the pitch is controlled to maximize energy capture. The pitch system also provides for overspeed protection in the event of loss of grid or similar fault.

Figure 2. Power Curve for the WEI6K Wind Turbine

The current production cost of the WEI6K was estimated from actual volume wholesale pricing of purchased components and quotations and estimates for fabrication of the remaining components. Working with staff at NWTC, we developed estimates of the balance of station costs from which we could determine the expected initial capital cost of an installed WEI6K turbine. The solicitation under which this grant was selected stipulated that a fixed charge rate of 8.55% be employed to determine the annualized capital cost from the initial capital cost. Again with help from NWTC staff we also estimated the expected annual operations and maintenance expenses, which, when combined with the annualized capital cost, result in an estimate of the annualized cost of ownership for the wind turbine. These figures are summarized in Table 2, which also summarizes the cost of energy analysis for the WEI6K Turbine. The turbine was designed with both a monopole steel tower and a guyed lattice tower. However, recent escalations in steel prices substantially increased the cost of the monopole tower from the time the project began. This had a very deleterious effect on the competitiveness of that configuration.

For the NREL Reference Site, with a mean wind speed of 5.35 m/s at 10 m height, the turbine is predicted to generate electricity at a levelized cost of energy of between 9.7 and 11.9 ¢/kWh, depending upon which tower is used. At an IEC Class IIA site, with an average wind speed of 8.5 m/s at hub height, the turbine would generate at a COE between 7.3 and 8.9 ¢/kWh. The lowest of these numbers is presently competitive with retail electricity rates in most of the country, or will be soon as electricity rates rise. The 8.9 ¢/kWh is still competitive with retail rates in many regions of the country with high electricity costs. The NREL Reference Site numbers are generally not competitive in our estimation.

Table 2. Cost of Energy Analysis

	Monopole Tower	Guyed Lattice Tower	Proposal/ Kickoff
Annualized Cost	\$ 2,539	\$ 2,074	\$ 1,891
Net Annual Energy Production			
NREL Ref. Site			
GAEP (kWh/yr)	23748		
Losses (5%)	-1187		
Unavailability (5%)	-1187		
NAEP (kWh/yr)	21373		23,755
IEC Class IIA			
GAEP (kWh/yr)	31598		
Losses (5%)	-1580		
Unavailability (5%)	-1580		
NAEP (kWh/yr)	28438		29,373
Cost of Energy			
NREL Ref. Site	\$ 0.119	\$ 0.097	\$ 0.080
IEC Class IIA	\$ 0.089	\$ 0.073	\$ 0.064

Therefore, we are encouraged by the fact that – without trying to be optimistic with respect to cost or performance – we are able to design a turbine that is competitive. However, it must be recognized at the same time that we may be limited in our choice of towers to a configuration that may be aesthetically displeasing to many potential customers. Moreover, superior performance is limited to relatively high-wind IEC Class II sites.

Substantial cost savings remain to be achieved in the design, and the energy capture of the system can be increased. As seen in Table 2, the performance presently being predicted for the turbine is falling 3-10% below the performance predicted at the time of the proposal. This is resulting from two factors: lowered power coefficients due to inappropriate choice of airfoil and energy lost to turbulence. Both factors are discussed further in the next chapter, but we believe that both can be addressed to increase the energy capture of the wind turbine by up to 10%. This will result in further improvements in the cost of energy.

2. Loads and Performance Analysis

2.1. Standards, Load Cases and Safety Factors

The WEI6K turbine has been designed and analyzed in conformance with IEC Standard 61400-1, Edition 3, Class II-A. This prescribes a mean annual wind speed at hub height of 8.5 m/s. The one exception to this standard is that we have used the mean turbulence intensity of 18% that corresponded to Class A conditions in the Edition 2 of this standard. Table 3 summarizes the operating environment for the wind turbine.

Table 3. Summary of WEI6K Operating Environment

IEC Wind Class	II-A (Edition 2)
Mean Hub Height Wind Speed	8.5 m/s
Mean Turbulence Intensity	18%
Rated Wind Speed, V_r	9 m/s
Cut-in Wind Speed, V_{in}	4 m/s
Cut-out Wind Speed, V_{out}	25 m/s
1-Year Extreme Wind Speed, V_{e01}	48 m/s
50-Year Extreme Wind Speed, V_{e50}	60 m/s

Table 4 summarizes the IEC-prescribed Design Load Cases (DLCs). Those marked in blue are ones that have been examined as part of the preliminary design of the WEI6K. This includes most of the ones that we consider to be critical. Table 5 summarizes the IEC wind conditions referenced in Table 4. We employed the IECWind program available from the National Wind Technology Center to generate these wind input files. At the time this analysis was conducted, only the IEC 61400-1 Edition 2 version of IECWind was available. For DLC1.2, we employed the SNWind3D program to generate three independent sets of 10-minute full-field turbulence time histories for each of the mean wind speed bins.

The following is a brief summary of the cases that have been skipped to date and the reasons for doing so:

- DLC 1.3: Extreme Turbulence Model: ETM is new to Edition 3, and the version of IECWind that includes the ETM was published too late to be used for this analysis.
- DLCs 2.2 and 2.4: We believe that our present approach to modeling DLC2.1 makes these two cases redundant.
- DLC 3.3: This analysis is pending at the time of this report.
- DLCs 6.2 and 7.1: Loss of electrical network or fault conditions while parked are irrelevant to our turbine. The parking brake defaults to the closed condition with loss of power or appropriate faults.
- DLC 6.4: Reserved for next phase of design.
- DLC8.1: Reserved for the next phase of design, pending more detailed definition of the assembly and maintenance procedures.

Table 6 summarizes the partial safety factors for loads as required by IEC. No safety factor is required for fatigue damage equivalent load calculations.

Table 4. Summary of Required & Completed Design Load Case Analyses

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors	Completed PDR?
1) Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N	V=5, 7, 9, 11, 13, 15, 17, 19, 21, & 23 m/s
	1.2	NTM $V_{in} < V_{hub} < V_{out}$		F	*	
	1.3	ETM $V_{in} < V_{hub} < V_{out}$		U	N	NO
	1.4	ECD $V_{hub} = V_r, V_r \pm 2\text{m/s}$		U	N	V=7, 9, 11 m/s $\pm$ Direction
	1.5	EWS $V_{in} < V_{hub} < V_{out}$		U	N	V=9, 25 m/s $\pm$ Shear, H & V
	Old 1.8	EDC $V_{hub} = V_r, V_{out}$		U	N	V=9, 25 m/s $\pm$ Direction
2) Power production plus occurrence of fault	2.1	NTM $V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N	V=7, 9, 11, 16, & 21 m/s
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A	NO
	2.3	EOG $V_{hub} = V_r \pm 2\text{m/s}$ and V_{out}	External or internal electrical fault including loss of electrical network	U	A	V=7, 9, 11, & 25 m/s
	2.4	NTM $V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*	NO
3) Startup	3.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*	V=7, 9, 11, 16, & 21 m/s
	3.2	EOG $V_{hub} = V_{in}, V_r \pm 2\text{m/s}$ and V_{out}		U	N	V=8 m/s
	3.3	EDC $V_{hub} = V_{in}, V_r \pm 2\text{m/s}$ and V_{out}		U	N	NO
4) Normal shutdown	4.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*	V=7, 9, 11, 16, & 25 m/s
	4.2	EOG $V_{hub} = V_r \pm 2\text{m/s}$ and V_{out}		U	N	V=7, 9, 11, & 25 m/s
5) Emergency shutdown	5.1	NTM $V_{hub} = V_r \pm 2\text{m/s}$ and V_{out}		U	N	V=7, 9, 11 m/s
6) Parked (standing still or idling)	6.1	EWM 50-year recurrence period		U	N	Yes
	6.2	EWM 50-year recurrence period.	Loss of electrical network connection	U	A	N/A?
	6.3	EWM One-year recurrence period	Extreme yaw misalignment	U	N	EWM01 $\pm$ Yaw & $\pm 30^\circ$ Yaw
	6.4	NTM $V_{hub} < 0.7 V_{ref}$		F	*	NO
7) Parked and fault conditions	7.1	EWM One-year recurrence period		U	A	N/A
8) Transport, assembly, maintenance and repair	8.1	To be stated by the manufacturer		U	T	NO
	8.2	EWM One-year recurrence period		U	A	NO

Table 5. Summary of Wind Models for DLCs

DLC	Design load case
ECD	Extreme coherent gust with direction change (see IEC 61400-1 Section 6.3.2.5)
EDC	Extreme direction change (see IEC 61400-1 Section 6.3.2.4)
EOG	Extreme operating gust (see IEC 61400-1 Section 6.3.2.2)
EWM	Extreme wind-speed model (see IEC 61400-1 Section 6.3.2.1)
EWS	Extreme wind shear (see IEC 61400-1 Section 6.3.2.6)
NTM	Normal turbulence model (see IEC 61400-1 Section 6.3.1.3)
ETM	Extreme turbulence model (see IEC 61400-1 Section 6.3.2.3)
NWP	Normal wind profile model (see IEC 61400-1 Section 6.3.1.2)

Table 6. Partial Safety Factors for Loads, γ_f , as per IEC 61400-1 Ed. 3

Unfavorable loads			Favorable loads
Type of design situation			All design situations
Normal (N)	Abnormal (A)	Transport and erection (T)	
1.35*	1.1	1.5	0.9
<p>* For design load case DLC 1.1, given that loads are determined using statistical load extrapolation at prescribed wind speeds between V_{in} and V_{out}, the partial load factor for normal design situations shall be $\gamma_f=1,25$.</p> <p>If, for normal design situations, the characteristic value of the load response $F_{gravity}$ due to gravity can be calculated for the design situation in question, and gravity is an unfavourable load, the partial load factor for combined loading from gravity and other sources may have the value</p> $\gamma_f = 1,1 + \varphi \zeta^2$ $\varphi = \begin{cases} 0,15 & \text{for } DLC1.1 \\ 0,25 & \text{otherwise} \end{cases}$ $\zeta = \begin{cases} 1 - \left \frac{F_{gravity}}{F_k} \right ; & F_{gravity} \leq F_k \\ 1; & F_{gravity} > F_k \end{cases}$			

2.2. Description of the Dynamic Model

All dynamic simulations of the WEI6K turbine have been performed using FAST version 5.1. Table 7 summarizes the degrees of freedom that are active in the FAST model. Three blade modes, two tower modes, and the generator are the only degrees of freedom in the model. The blade mode shapes and frequencies and the tower mode shapes and frequencies are described in Chapters 5 and 7, respectively. The turbine is active yaw, and yaw control was not modeled in

the preliminary design simulations, so the yaw DOF was left off. As noted in Chapter 3, the aerodynamic rotor is coupled directly to the generator rotor by way of the rotor hub, and the modal analysis of the hub showed it to be extremely stiff with respect to frequencies of interest in this study, so the drivetrain rotational flexibility DOF was also left off. The turbine does not employ rotor teeter. Aeroacoustics calculations are on-going at the time that this report is being prepared, but as part of the general analyses, the aerodynamic noise was not calculated.

Table 7. Active Degrees of Freedom in FAST 5.1 Model of the WEI6K Turbine

----- FEATURE FLAGS -----		
TRUE	FlapDOF1	- First flapwise blade mode DOF (flag)
TRUE	FlapDOF2	- Second flapwise blade mode DOF (flag)
TRUE	EdgeDOF	- First edgewise blade mode DOF (flag)
False	TeetDOF	- Rotor-teeter DOF (flag) [unused for 3 blades]
False	DrTrDOF	- Drivetrain rotational-flexibility DOF (flag)
TRUE	GenDOF	- Generator DOF (flag)
False	YawDOF	- Yaw DOF (flag)
TRUE	TwFADOF1	- First fore-aft tower bending-mode DOF (flag)
False	TwFADOF2	- Second fore-aft tower bending-mode DOF (flag)
TRUE	TwSSDOF1	- First side-to-side tower bending-mode DOF (flag)
False	TwSSDOF2	- Second side-to-side tower bending-mode DOF (flag)
True	CompAero	- Compute aerodynamic forces (flag)
False	CompNoise	- Compute aerodynamic noise (flag)

The following is a description of the settings for the FAST Simulation control parameters:

- Integration time step, DT, is 0.0025 sec for all simulations
- Yaw Control Mode, YCMode, is 0 (none) for all simulations
- Pitch Control Mode, PCMode, is 1 for user-defined for all simulations. Further details are provided below.
- Variable speed Control, VSContrl, is 0 (none) for all simulations.
- Generator Model, GenModel, is 3 (User defined) for all simulations. Further details are provided below.
- Method to start the generator, GenTiStr, was TRUE for timed start for normal simulations, and was set to FALSE for startup simulations, in which case the starting of the generator was controlled by the user-defined generator model.
- Method to stop the generator, GenTiStp, was set to FALSE (when generator power goes to zero) for normal simulations, in which case shutdown was controlled by the user-defined generator model, and was set to TRUE (for timed shutdown) for simulating loss of grid and emergency shutdown cases.
- Generator speed to turn on the generator for startup, SpdGenOn, is 150.0 rpm.
- HSS Brake Model, HSSBrMode, is 1 for the simple model
- Initial or fixed rotor speed, RotSpeed, is set to 150 rpm for normal simulations, and is set to 0 for startup simulations.
- All other initial conditions are set to zero.

Table 8 summarizes the loads and motion output from the FAST5.1 simulations.

The FAST model of the blade and the AeroDyn input file are based on the aerodynamic and structural properties described in detail in Chapter 5. The FAST model of the tower is based on the structural properties described in Chapter 7.

Table 8. Summary of FAST 5.1 Output

----- OUTPUT -----	
True	SumPrint - Print summary data to "<RootName>.fsm" (flag)
True	TabDelim - Generate a tab-delimited tabular output file. (flag)
"ES11.4E2"	OutFmt - Format used for tabular output except time. Resulting field should be 10 characters. (quoted string) [not checked for validity!]
10.0	TStart - Time to begin tabular output (s)
6	DecFact - Decimation factor for tabular output [1: output every time step] (-)
1.0	SttsTime - Amount of time between screen status messages (sec)
0.0	ShftGagL - Distance from rotor apex [3 blades] or teeter pin [2 blades] to shaft strain gages [positive for upwind rotors] (meters)
5	NBlGages - Number of blade nodes that have strain gages for output [0 to 5] (-)
1,2,4,6,8	BldGagNd - List of blade nodes that have strain gages [1 to BldNodes] (-)
	OutList - The next line(s) contains a list of output parameters. See OutList.txt for a listing of available output channels, (-)
"HorWindV, HorWndDir"	- Horizontal Hub-Height Wind Speed (m/s) and Direction
"RotSpeed"	- Rotor speed (rpm)
"GenPwr, GenTq"	- Electrical Power, generator torque
"Azimuth"	- Rotor azimuth angle
"BldPitch1,BldPitch2,BldPitch3"	- Pitch of Blades 1, 2, and 3 (deg)
"OoPDefl1,OoPDefl2,OoPDefl3"	- Out of plane tip deflections of Blades 1,2,3
"TipDxb1,TipDxb2, TipDxb3"	- Flapwise tip deflections of Blades 1, 2, 3
"TTDspFA,TTDspSS"	- Fore-aft, side-to-side tower top displacement"
"RootFxb1,RootFyb1"	- Blade 1 Root Forces, flap & edge axes
"RootMxb1,RootMyb1,RootMzb1"	- Blade 1 Root Moments, flap & edge axes
"RootMxc1,RootMyc1"	- Blade 1 Root Moments, in-plane and out-of-plane
"RotThrust,LSShftFya,LSShftFza"	- Low Speed Shaft Rotating Forces
"RotTorq,LSSTipMya,LSSTipMza"	- Low Speed Shaft Torque, and rotating moments
"LSSTipMys,LSSTipMzs"	- Low Speed Shaft fixed moments
"YawBrFxp,YawBrFyp,YawBrFzp"	- Tower Top Fixed frame shear forces
"YawBrMxp,YawBrMyp,YawBrMzp"	- Tower Top Fixed frame Moments
"TwrBsFxt,TwrBsFyt,TwrBsFzt"	- Tower Base Shear Forces
"TwrBsMxt,TwrBsMyt,TwrBsMzt"	- Tower Base Moments
"Spn1MLxb1,Spn1MLyb1"	- Spanwise loads on Blade 1 at gage 1
"Spn2MLxb1,Spn2MLyb1"	- Spanwise loads on Blade 1 at gage 2
"Spn3MLxb1,Spn3MLyb1"	- Spanwise loads on Blade 1 at gage 3
"Spn4MLxb1,Spn4MLyb1"	- Spanwise loads on Blade 1 at gage 4
"Spn5MLxb1,Spn5MLyb1"	- Spanwise loads on Blade 1 at gage 5

The operation of the pitch control system is described in detail in Chapter 6. In the synchronous power generation mode, the pitch controller attempts to maximize power production when the wind speed is above the cut-in value and below the rated value by adjusting the pitch to the optimal value for the electric power being generated. When the wind speed is above the rated value it attempts to limit the power production to the rated 6 kW value by pitching the blades to feather. The pitch controller described in Chapter 6 was implemented into FAST through custom versions of the subroutines Control and CTRL4 called from within FAST. This routine implements the full functionality of the pitch system, including normal operation as well as startup and shutdown modes.

The generator is described in detail in Chapter 4. The generator modeled in FAST for the purposes of loads simulations was implemented by modifying the FAST subroutines DrvTrTrq and UserGen to implement the generator characteristics described in that chapter.

2.3. Predicted Power Performance

Figure 2 summarizes the electrical power performance results obtained from the FAST simulations. The turbulent simulation results are taken from the DLC 1.2 runs. The maximum power observed during any simulation was 10.85 kW in DLC3.2. This was very transient and is within safe margins for the generator design. Although all turbines shed some power when operating in turbulent conditions near the Region 2-3 transition, we believe that this turbine as modeled is shedding too much power. We are losing between 4-5.5% of our energy capture due to this behavior, which means we are losing around 10% of our energy capture below rated. We would not have expected a value of more than 2-3% of the power below rated. In gusty conditions near rated, we believe that the pitch system is chasing increasing gusts by driving the pitch to feather, such that when the wind drops back, the power drops precipitously. As part of the next stage of design, one of the major priorities will be to tune the operation of the pitch system in this region to lessen this problem.

2.4. Summary of Ultimate Loads, Fatigue, and Deflections

Ultimate and fatigue damage equivalent loads were predicted for the WEI6K turbine using the FAST simulations. Fatigue cycles were calculated from the DLC1.2 time histories using an in-house rainflow cycle counting routine. The results from the three independent sets of turbulent inflow files were added to provide a total of cycles for each component of load, assuming 30-minute total simulations. Then the fatigue damage equivalent loads were calculated using the Palmgren-Miner method.

Binned fatigue cycles proved useful for the analysis of several components, including the hub, main shaft bearings, and the yaw deck. Plots of binned cycles were produced for all components of loading. Several mechanical components require calculation of so-called "Revs at Levs" of reaction loads, or the number of revolutions in the life spent at a given mean load level. These reaction loads have been calculated for the main shaft bearings and the yaw torque for analyzing the yaw drives.

The maximum blade tip deflection was 149 mm observed in DLC1.4, the Extreme Coherent Gust with Direction Change at 11 m/s mean wind speed. Static tip-tower clearance is 545 mm, so we are consuming only 27% of the static clearance.

3. Turbine Mechanical Systems

The WEI6K turbine is an integrated direct-drive machine that eliminates the gearbox and combines the main frame with the generator housing. The turbine mechanical assembly – everything above the tower except for the rotor blades – is illustrated in several cut-away views in Figure 1.

The main components of this system are:

- Generator Housing Assembly
- Generator Support Shaft and Main Bearings
- Generator Rotor Assembly
- Blade Housing (Hub)
- Blade Pitch System
- Disk Brake Assembly
- Tower top interface and Yaw System

The generator housing serves as the main frame for this system. This item is cast iron and machined. The generator rotor assembly is fixed to the aft end of the hub. Therefore, the system has no rotating main shaft; the hub and generator rotor are integrated. The generator support shaft is machined from 5” steel tubing to the required dimensions and mounted to the housing. This is a fixed shaft. The shaft supports a pair of bearings that in turn support the blade housing (hub). The two ball bearings are each factory lubricated and sealed. Commercially available bearings have been selected for the application. Ultimate bearing loads are calculated from the reaction loads at the bearing required to balance the vector sum of the components of hub ultimate loads, calculated assuming that all components of ultimate hub loads occur simultaneously. This is a very conservative calculation of the loads that will be revisited in subsequent design iterations. These loads are applied at hub center and the resulting reactions are compared to the bearing’s static load capacity.

A similar calculation was performed to determine the fatigue damage equivalent loads for the bearings. At the time the bearing analysis was conducted, the dynamic simulations were not set up to output actual main shaft bearing reaction loads. Hence, we did not have simulated time histories of bearing reaction loads which we could rainflow count to produce a distribution of cycles and range. Therefore, we employed the binned distributions of cycles and range for the various components of rotor loads to calculate vector sums for each bin to produce the binned distribution of cycles and range for the bearing reaction. From this we employed Miner’s rule to calculate a fatigue damage equivalent bearing load.

Ball bearing life is substantially affected by thrust loads. The selection of factors X, Y depend on the ratio of radial to axial load and the ratio of static capacity to axial load. The general equation for adjusting the radial load is:

$$P_r = XF_r + YF_a$$

X = constant from manufacturers catalog

F_r = computed radial load

Y = constant from manufacturers catalog

F_a = computed axial load

The basic life equation, yielding life in hours, is

$$L_{10} = \left(\frac{C}{P_r} \right)^e \cdot \frac{33.333}{n}$$

Where: C = basic dynamic capacity

P_r = equivalent fatigue radial load

e = bearing exponent = 3.0 (ball bearings)

n = shaft rpm = 150

This calculation for the WEI6K turbine shows an estimated life of no less than 148,000 hours, which corresponds to roughly 20 years of operation in IEC Class II conditions, the required life-time.

The rotor hub consists of a main casting that is machined to receive the blade bearings and pitch mechanism and the central rotor bearings. The hub is illustrated in Figure 3. The rotor body is cast from ductile iron per EN FJS-400-18U-LT, a material grade that maintains good impact properties in extremely cold environments. Table 9 summarizes the material properties employed in the structural analysis.

The hub was analyzed structurally using the finite element method in the Cosmos/M commercial software with the FFEPlus solver. The Finite Element Model of the hub is illustrated in Figure 3. The model was meshed with 61182 elements and 112260 nodes.

Ultimate and fatigue loads were calculated as summarized in Chapter 2. For the ultimate analysis, the blade forces are assumed at their maximum absolute value, applied simultaneously. Analysis is made for a single blade position using the blade root station loads and for the shaft loads applied as moments to shaft bearing datum and reacted by blade bores.

For ultimate loads, the allowable stress is based on the yield properties with the material partial safety factor $\gamma_m = 1.1$. The safety factor for strength is given by

$$SF_{str} = \frac{S_u}{\sigma_u \cdot \gamma_M}$$

and was found to exceed the minimum combined safety factor as required by Germanischer Lloyd for certification purposes.

Figure 3. 3D view of hub

Table 9. Hub Material properties

EN-GLS-400-18U-LT Per DIN 1563			
Item	Thickness of section	N/mm ²	psi
Ultimate strength S_u	<30	400	58,000
	<60	390	56,550
	>60	370	53,650
Yield strength S_y	<30	240	34,800
	<60	220	31,900
	>60	230	33,350
Fatigue @ $1.3 \cdot 10^9$	10	62	9,000

The fatigue limit is derived using the following factors:

S_f Fatigue allowable at design cycles (1.3×10^9)

S_u Reliability factor = .83

S_d Technical delivery (quality) = .85

γ_m Material partial safety factor, fatigue = 1.0

From this, we compute the allowable stress:

$$S_e = \sigma_{allow} = S_f \cdot \frac{S_u \cdot S_d}{\gamma_m}$$

The fatigue damage equivalent stress in the hub, based on an equivalent von Mises stress evaluation, is used to calculate the safety factor for fatigue damage in the hub, given by

$$SF_{body_fatigue} = \frac{S_e}{\sigma_f \cdot \gamma_M}$$

The expected life of the hub was found to well exceed the required 20 year life of the turbine.

Modal analysis of the hub shows that the hub is extremely stiff with respect to the overall system dynamics, with the lowest natural frequency (302 Hz) two orders of magnitude higher than the shaft frequency (2.5 Hz), and an order of magnitude higher than the blade frequencies modeled in the present simulations. The results indicate that it is not necessary to model hub/shaft dynamics in our simulations.

The blade housing (hub) both supports the blades and the pitch system. The WEI6K features an active motorized pitch system.

The yaw system attaches directly to the base of the Generator Housing and serves as the interface between the main frame and the tower top. The WEI6K turbine employs an active, electromechanically motorized yaw control system instead of the passive yaw control system typically employed on small wind turbines. While this does introduce extra electromechanical systems, it eliminates the tail found on other small turbines. Ample data is available in the published literature to suggest that tails only inaccurately orient turbines in to the wind and that the presence of the tail can lead to buffeting of the turbine in the yaw degree of freedom, thereby increasing loads and fatigue on the entire system.

The WEI6K active yaw system consists of the following components:

- Yaw motor
- Gearhead reducer
- Yaw gears, final drive
- Yaw bearings
- Control system

The bearing selection is made to space and availability constraints. The diameter selected is larger than optimum for bearing life in order to integrate a yaw gear in the bearing race. The larger diameter is also influenced by availability of standard product of which this is the smallest size available as a “catalog” slewing ring bearing.

Ultimate design loads for the bearing have been derived by vector summation of the ultimate tower top load components as if the limiting design cases for all components occurred simultaneously. The resulting reactions are compared to the static load capacity of the bearing. A similar calculation was performed to determine the fatigue damage equivalent loads for the yaw bearing. At the time the bearing analysis was conducted, the dynamic simulations were not set up to output actual yaw bearing reaction loads. Hence, we do not have simulated time histories of bearing reaction loads which we can rainflow count to produce a distribution of cycles and range. Therefore, we employed the binned distributions of cycles and range for the various components

of tower top loads to calculate vector sums for each bin to produce the binned distribution of cycles and range for the yaw bearing reaction. From this we employed Miner's rule to calculate a fatigue damage equivalent yaw bearing load. The resultant fatigue damage equivalent load is used to select the appropriate bearing. The applied moment load is just 5% of the bearing rating. The radial load is 2% of rated. These numbers place the rated load below fatigue limit, indicating an infinite life. We have determined that this calculation is very conservative. In future iterations of the design, we will update the analysis to calculate the yaw bearing reaction at each time step, from which we can determine the number of cycles of each load level ("Revs at Levs") that are experienced by the yaw bearing.

Miner's rule is employed to calculate a fatigue damage equivalent torque from the yaw torque load spectrum. This equivalent torque is in turn used to determine the gear life of the final drive gears and for sizing the servo drive and gear head reducer.

The yaw system is designed for a tower top that is 12 inches (304.8 mm) in diameter, a constraint to the final drive gear diameter. We have entertained both 12-inch and 16-inch tower tops in the present preliminary design, and the current yaw system design can easily accommodate a larger tower diameter simply by changing the bearing diameter. This issue will need to be revisited during the detail design stage to ensure consistency in these features.

4. Electrical Systems

One of the key distinguishing features of the WEI6K turbine has been, from the outset of the design, the use of a permanent-magnet synchronous AC generator. The motivation for this design decision is avoiding the requirement for expensive, inefficient, and generally unreliable power electronics for performing full power conversion. Most of the small turbines presently on the market employ direct-drive permanent magnet generators in order to avoid the use of gearboxes, which are prone to failure and require frequent maintenance. Traditionally, however, manufacturers have not gone to the trouble of trying to synchronize those generators to the grid, allowing them to generate variable frequency, variable voltage output which then has to be rectified and inverted for 60 Hz usage. Many of these turbines were originally designed for off-grid application, however, where such operation is necessary, but the power electronics required to operate these turbines grid-connected unnecessarily and significantly inflates their costs to consumers. Given the grid-connected application of the present turbine, we decided that the best approach is to employ a synchronous generator tied directly to the grid.

Use of a synchronous generator necessitates some means of synchronizing the turbine to the grid, which requires fairly accurate regulation of the shaft speed during startup. This regulation is effected through blade pitch regulation. Therefore, the WEI6K employs a sophisticated controls system to monitor shaft speed (during startup) and power and regulate the blade pitch accordingly to maintain optimal performance.

4.1. Direct Drive Synchronous Generator

A direct drive permanent magnet (PM) synchronous generator operating at 60 Hz electrical frequency has a fixed mechanical shaft speed n given by

$$n=7200/n_p \text{ (rpm)}$$

where n_p is the number of magnetic poles in the machine structure. Since the number of magnetic poles is an even value integer the operating shaft speed of the machine is restricted to various fixed values given by the above equation. But the shaft speed n is also the blade rotation speed for the driving wind turbine. The optimum turbine rotational speed is limited to be within a small range of values determined by the operating wind speed and the turbine blade design (i.e. there is an optimum blade speed to wind speed ratio). Thus the choice of the number of magnetic poles n_p for the generator design must also be restricted to a small range of values.

In the present case the turbine shaft speed for the 6 kW machine was limited to an initial design range of 100 to 180 rpm, which results in a generator pole count range of 72 (at 100 rpm) to 40 (at 180 rpm). Trial generator designs were thus limited to this pole count range.

There are a great many possible PM generator configurations, but the present work addresses only one. The generator physical construction was modeled after the “unit pole” low speed PM

generator concept¹ developed in the USDOE WindPact Program. In the WindPact study many possible PM generator configurations were compared for use in low speed wind turbine applications. The machine construction selected for highest performance at least manufactured cost was the unit pole design.

The basic elements of a linear machine two pole segment for this construction are shown in Figure 4. Rotor magnet poles (rare earth, high strength Neodymium Iron Boron magnet material), in the form of rectangular blocks (the lowest cost format per unit of magnet mass) are constrained by inter-pole non-magnetic material wedges and ferromagnetic pole caps. This rotor pole construction is then mounted on a mild steel rotor back iron plate or yoke. The magnet pole caps perform two functions: magnet material confinement (radial retention in a rotary machine) and mitigation (reduction) of flux pulsations within the PM material due to the variation of flux path reluctance between radial paths through stator teeth and midway between stator teeth (the ferromagnetic pole caps effectively average out the low reluctance of the mid tooth path). The stator iron structure consists of laminations forming three teeth per rotor pole-pair and a flux return yoke. The phase coils are wound around individual teeth and are separated at a 120 electrical degree pitch so each coil serves as a phase winding in a balanced three-phase system.

Figure 4. Developed View of the Unit Pole Pair PM Generator Construction

¹ The term “unit pole” refers to a machine design that is based on optimization of a linear machine, single pole-pair segment. This pole-pair segment could then be applied to any large radius (large in comparison to the dimensions of the pole pair segment) in which the radius of curvature effects were small.

Optimization of the pole-pair unit segment shown in Figure 4 for a given pole pitch and attainable current density within the stator coils consists of varying the magnet thickness and width, the stator teeth width, yoke thickness, and slot depth, etc., in an attempt to maximize the developed tractive (x – directed) force between the stator and rotor per unit stack length (z – directed). In practice, there is no absolute optimum solution to this problem, other concerns preclude seeking true maximum force geometry. For example, very deep stator slots result in very large total slot currents (total ampere turns), which would indicate large tractive forces. But very deep slots also result in large leakage inductances for the stator coil windings. Large leakage inductances limit the machine short circuit current rating, which results in low pullout torque capabilities. The optimum structure we seek is then an “engineering optimum”, one in which many trade-offs are considered. In the present study the initial dimensions of the structure of Figure 4 were obtained by ratios to corresponding dimensions in WindPact final design unit pole machine. Slight changes were made to these resultant “scaled” dimensions after several finite element analysis (FEA) studies were conducted. The initial machine design was made for the 180 rpm 40 pole configurations, and the other machine design were then found by adjusting the x-directed dimensions for an assumed constant stator bore (inner diameter).

In the WindPact unit pole machine design the x-directed stress in the machine air gap, for reasonable coil current densities (which allowed for air cooling of the coils), approximately $6 A_{rms}/mm^2$ in the coil copper, approached 10 psi. But the WindPact machine unit pole segments are much larger than the corresponding segments in the present machine design. An air gap stress of 4 to 5 psi is thought to be a practical goal for the 6 kW machine in this program. For comparison, a standard industrial, 240/480 volt, integral horsepower induction motor achieves approximately 1 psi of air gap stress at rated output.

The NREL WindPact study included estimates of production costs for the proposed wind turbine PM generator structures. In the present work we also utilize this cost estimate methodology. Two spreadsheet programs have been used to estimate production costs. A first spreadsheet estimates the material content of a given generator design. It calculates the masses of the active material in the design, the laminations, the copper windings, and the permanent magnets. A second spreadsheet uses the results of the first to calculate the costs of the active materials, materials needed for support structures and the labor costs for fabrication and assembly. This second spreadsheet uses the costing methodology of the WindPact study.

For a given constant stator bore we calculate by magnetic FEA and use of the active component mass calculation spreadsheet (described in the previous section) the design results for each of the machines studied. The stack lengths of the designs were determined by specifying that the synchronous (steady-state) inductance of each machine phase be 33% of the base phase inductance L_B of a machine rated at a base power P_B of 6 kW, at the base electrical frequency f_{eB} of 60 Hz, with a terminal base voltage v_B of 208 Vrms line-to-line. A machine with a 33% inductance will have a short circuit (at the machine terminals) capability of 300% of the machine base current and a maximum short-term power generation capability of 300% of the machine base power. This maximum power capability is a design specified value, and ensures that the generator will not fall out of synchronous operation during short-term transients due to gusting wind conditions or power system mis-operation. Note that in these statements of capability it is assumed that the

machine winding resistance is very small in value in comparison winding synchronous reactance. This is true for all machines studied.

Electrical efficiency over the power range of operation for each trial machine can be determined by solving the per phase phasor equivalent circuit shown in Figure 5. Resistors R_c and R_s account for stator core (iron) loss and copper winding loss, respectively. Inductance L_s is the self inductance of the phase windings, Flux linkage ψ_m is the magnitude of the flux linkages in each phase winding due to the rotor magnets and the angular frequency ω_e is the steady state electrical radian frequency of operation, $\omega_e = 2\pi \cdot 60 = 377 \text{ (sec}^{-1}\text{)}$. The rotor electrical lead angle δ is the angle by which the magnet induced back emf of the machine $e_m = \omega_e \psi_m$ leads the terminal voltage v_s .

Figure 5. Per Phase Equivalent Circuit of the PM Generator

The per phase phasor circuit of Figure 5 is solved in per unit by first assuming a value of δ and then finding the internal current i_{ms} and voltage e_{ms} by means of a Thevenin equivalent circuit approach. The circuitry to the right of the inductance L_s is reduced to an equivalent resistance $R_e = R_s R_c / (R_s + R_c)$ and an equivalent voltage $v_e = v_s R_c / (R_s + R_c)$. The circuit of Figure 5 then is simplified to that of Figure 6. Internal current i_{ms} is solved for as $i_{ms} = (e_m(\delta) - v_e) / (R_e + j\omega_e L_s)$. And internal voltage e_{ms} is found as $e_{ms} = v_e + i_{ms} R_e$. The stator terminal current i_s is then $(e_{ms} - v_s) / R_s$ and the core loss current i_c is e_{ms} / R_c . The machine input (shaft) power P_m is $\text{Re}(e_m i_{ms}^*)$ and the output (terminal) power P_s is $\text{Re}(v_s i_s^*)$, where $\text{Re}(x)$ is the real part of the complex variable x and x^* indicates the complex conjugate of x . The terminal VAR or reactive power output of the machine is given by $\text{Im}(v_s i_s^*)$, where $\text{Im}(x)$ is the imaginary portion of x .

The results show that the heavier the machine, the more the cost to produce it, and so machine cost rises with pole count, roughly in linear fashion. When taken as a total system, wind turbine and electrical generator, weighing total net energy capture over the input wind speed distribution and initial fabrication costs, it was decided to pick the 150 rpm package for further analysis and study. For the chosen machine, the electrical efficiency $\eta = P_s / P_m$ exceeds 90% when the output power rises above approximately 25% of rated power and exceeds 94% when P_s is above 50% of rated.

The electromagnetic expected performance of this machine has been calculated by magnetic finite element analysis (FEA). Magnetic FEA calculations were also used to calculate the machine

winding inductances. For a given set of test currents in the machine windings, the FEA studies determined the amount of flux due to these currents coupled back into the winding. The ratio of flux to exciting current then was the winding inductance per unit axial length of machine laminations. The stipulation that the per-phase inductance be 33% of the base value of inductance then determined the required stack length of the machine.

Figure 6. Reduced Order, Simplified Equivalent Circuit of the PM Generator

4.2. Grid Intertie

The three-phase PM synchronous generator described in Section 4.1 can be directly connected to a three-phase electrical grid, or its stator winding sets can be internally reconnected such that it can feed either two-wire or three-wire single-phase systems. The two- and three-wire single-phase connection schemes are shown in Figure 7. The most common single-phase configuration is expected to be the three-wire system of Figure 7(b). For balanced circuit loading on the two single-phase circuits, there would be no net neutral wire current, so the two- and three-wire systems would then operate identically. As far as the PM machine is concerned, current flow in the neutral wire has no effect on the air gap torque (neutral wire is zero sequence current) so both single-phase systems are nearly identical.

In the single-phase system the local loads, on the user side of the meter and the point of common connection (PCC) to the local utility, would be split into two groups. Loads that could be potentially wind supplied in a stand-alone system (total rating less than or equal to the 6 kW output rating of the wind machine) would form one group. And loads that are designated to not be fed should the utility system be disconnected, no matter the state of the wind turbine, would form a second group. The potential wind backed loads and the wind generator would tie together at the Wind Machine Panel. This panel would then be connected to the Main Panel through an isolation contactor. This contactor would in general always be closed when the local utility feed is active.

Should the utility feed be interrupted, the Main Control Electronics unit detects the interruption (by means of voltage and power flow monitoring) and opens the isolation contactor to prevent back feeding even a portion of the non-utility fed local grid. In that way “islanding” in the local grid would be prevented.

(a) Single-Phase, Two-Wire Connection of the Proposed Three-Phase PM Generator

(b) Single-Phase, Three-Wire Connection of the Proposed Three-Phase PM Generator

Figure 7. Proposed Connections for the Three-Phase PM Generator

The connection of the wind generator windings to the Wind Machine Panel is through a set of TRIAC-like solid-state switches. These switches will be under control of a microprocessor in the Main Control Electronics unit and in this report will be referred to as the generator “closing switches.” When the wind speed is below the cut in value, or above the safe operation upper limit value, or when the turbine is to be shut down for maintenance, these switches will be open. When the wind speed is within the safe operating region, these switches will be fully closed. The operation to transition these switches from the open state to the closed state is always done when the electrical frequency and phase of the spinning PM machine voltages are very close to the frequency and phase of the corresponding utility grid voltages. This closing operation is referred to as “synchronization”. These electronic switches can be opened at any time with no consideration for relative phasing or instantaneous frequency.

Each local electrical utility has (or will soon have) a specific set of requirements for interconnection of small generators to their distribution system lines. Generally these specifications follow the technical guidelines set forth in IEEE Standard 1547, “Standard for Interconnecting Distributed Resources with Electing Power Systems.” This standard is intended to provide a uniform basis for the requirements relevant to the performance, operation, testing, safety considerations, and maintenance of an interconnection between a distributed resource (e.g. wind generator) and the utility grid. The main concerns of IEEE 1547 are the quality of the power injected into the utility system at the PCC when the wind generator is operating and enforcement (with a measure of certainty) of methods of operation such that the condition of islanding will never occur. Our proposed system will meet all stipulations contained in IEEE 1547 for a distributed resource generation system of less than 30 kW rating. No additional hardware will be required to meet the guidelines of the 1547 Standard.

Three stipulations of IEEE 1547 are of particular note for our direct-connect PM synchronous generator: (we paraphrase the 1547 language to make it apply to our proposed system directly):

1. Synchronization, IEEE 1547 Section 4.1.3. The synchronous generator shall synchronize with the local electric power system without causing a voltage fluctuation at the PCC of greater than $\pm 5\%$ of nominal voltage (i.e., ± 12 Vrms line-to-line in the single phase connection)
2. Voltage Disturbances, IEEE 1547 Section 4.2.1. The protection functions of the generator control and monitoring electronics shall measure the effective (RMS) or fundamental frequency value of each phase-to-phase voltage at the generator connection bus. When any of the measured voltages is in per unit ranges given in the table below, the generator shall cease to energize the local electric power system within the clearing times indicated. Clearing time is the time between the start of the abnormal voltage conditions and the time at which the generator is completely disconnected.

Voltage range (per unit)	Clearing time (60 Hz cycles)
$v < 0.50$	10
$0.50 < v < 0.883$	120
$1.10 < v < 1.20$	60
$1.20 \leq v$	6

3. Frequency Disturbances, IEEE 1547 Section 4.2.2. All generators shall follow the local electric power system frequency (nominally 60 Hz) such that the frequencies of the voltages at the PCC or the generator connections point remains in the range of 59.3 Hz to 60.5 Hz.

This last restriction, frequency control during synchronization and wind gusts, requires further discussion. It is important to understand that the electrical frequency of the rotor is not the electrical frequency of the voltages at the PCC. It can be easily shown that an angular variation at the machine rotor with respect to the power system reference (constant angular speed of $2\pi \cdot 60 = 377$ radius/sec) is reduced by at least the inverse value of the system stiffness ratio at the PCC. For a very low ratio of only 4, we must maintain the shaft speed within 5 rpm of nominal in order to maintain the frequency of the voltages at the PCC within 0.5 Hz. Our simulations of grid synchronization show that we can easily maintain the speed within this range during synchronization operations.

The electronic TRIAC function closing switches which will close to initiate synchronization between the utility grid and the PM wind generator, can be switched to a fully closed state in a very small fraction of a 60 Hz electrical cycle. In all aspects of operation that affect machine torque and rotor speed these switches are essentially instantaneous in their transition from a blocking to a conducting state. The system control microprocessor that commands these switches to close is also fast-acting, with respect to the period of a fundamental 60 Hz waveform.

For example, a decision to close the synchronizing switches can be implemented (gates of switches energized) in less than one hundred microseconds. In large generator installations the closing switch is a mechanical contactor or circuit breaker. These mechanical switches are much slower in operation; i.e. the time required to fully close, measured from the time of the decision to close to the time of complete contact closure. In addition, mechanical switches are slower to open, and in fact cannot be repeatedly cycled, close-open-close-open because of arc heating at the electrical contact spots. There is no such restriction for the electronic switches used in our proposed system, as long as the synchronization electrical /mechanical transient is kept under control (minimal excess heating due to transient overcurrents in the synchronization process). Thus for electronic switching for synchronization, with minimal closing overcurrents, the entire synchronization sequence of events becomes almost a non-issue.

5. 3.2m Rotor Blade Design

5.1. Aerodynamic Design

All cross-sections of the rotor blade employ the NREL S822 airfoil. The S822 is a 16% thick airfoil, pictured in Figure 8. It achieves maximum thickness at around 30% chord, but maintains a thickness near the maximum over a substantial chordwise extent. This is good from structural considerations. The airfoil was specifically designed for use on the outboard portions of blades of length approximately 3-10 m. Our turbine falls on the low end of this range.

Figure 8. S822 Airfoil, 16% Thickness-to-Chord Ratio

Baseline two-dimensional aerodynamic performance data for this turbine was obtained from wind tunnel tests conducted by Dr. Michael Selig and his team at the University of Illinois at Urbana-Champaign. This data was provided to Wetzel Engineering in raw form by Selig. This data was somewhat rough in the sense that it exhibited peculiarities that were difficult to attribute to physical explanations. For example, there were individual data points where the lift or drag deviated substantially from the general trend in the vicinity of the point. Therefore, the data was cleaned slightly to produce the lift and drag results shown in Figure 9. While the airfoil performance suffers substantially at low Reynolds numbers when the angle of attack is near zero, the maximum lift-to-drag ratio achieved is not strongly affected by Reynolds number over the range 10^5 to $5 \cdot 10^5$, varying from around 35 to 40.

It is important to correct the two-dimensional airfoil data for three-dimensional effects, including most importantly the very strong radial flow effects that influence the performance in the inboard sections of the turbine. Towards this end, we employed a tool developed by Woodward Engineering for NWTC. This tool applies the Selig-Du correction and includes the Eggars C_D adjustment. One inputs the original two-dimensional airfoil characteristics, as well as the rotor diameter, shaft speed, wind speed, radial location of interest (as a percent of the rotor radius) and the chord length at the station of interest. Given a rotor diameter, the most important factors are the radial location and the chord length. These have a very strong influence on the magnitude of the three-dimensional corrections. The shaft speed and the wind speed had only secondary effects through their influence on the Reynolds number. Given our choice of design parameters, the corrections were negligible for radial stations outboard of 50%. Therefore, we applied the corrections to the 25%, 35%, and 45% spanwise stations. The magnitude of the correction suggested at the 25% spanwise station would have pushed the maximum lift to in excess of 2.5, a result of which we were skeptical. Therefore, we employed some judgment in using the corrections. Figure 10 illustrates the three-dimensionally corrected lift coefficients used in the FAST simulations.

Figure 9. Two-Dimensional Aerodynamic Characteristics of the S822 Airfoil

Figure 10. Three-Dimensionally Corrected Aerodynamic Data used in FAST Simulations

The contour optimization had a single Figure of Merit – maximize the annual energy production at an IEC Class II site. A common traditional way of optimizing rotor contour is to adjust the spanwise distribution of chord length and twist to maximize the power coefficient. One can nondimensionalize the problem by replacing the spanwise dimension with the fraction of the radius (r/R) and by replacing the local chord length at each spanwise station by the local solidity. For a given set of aerodynamic characteristics (i.e., a single pair of C_L - α and C_D - α curves), there is a single optimal distribution of local solidity and twist that will yield the maximum power coefficient *for each tip speed ratio*. The actual size of the turbine (and hence the chord lengths corresponding to local solidity), the wind speed, and the shaft speed will affect the Reynolds number, but over some reasonable range of these parameters corresponding to a real turbine design, these effects are typically secondary. Therefore, if we perform the optimization for a range of tip speed ratios, we will find the maximum power coefficient that can be produced at each, and from that we can find the combination of tip speed ratio and rotor planform and twist that will produce the maximum power.

This approach is ideal for the design of variable speed wind turbines, where the turbine shaft speed can be matched to the wind speed to maintain a nearly constant tip speed ratio over a wide range of wind speeds below rated. This ensures maximum energy capture. This approach is not ideal for the design of fixed speed turbines, where the tip speed ratio will vary dramatically with wind speed. The turbine will operate optimally at only one wind speed. However, the optimization described above tends to produce rotor designs with fairly narrow, peaky curves of C_p versus tip speed ratio. Therefore, the off-design performance tends to be much poorer. Nevertheless, this approach is still widely used, with the design point being picked as the operating conditions at some wind speed and shaft speed of importance, such as the rated wind speed.

For the present design of a fixed-speed, pitch regulated turbine, we have employed an entirely different approach to optimization. The rotor has been optimized to maximize energy capture over the entire range of below-rated wind speeds, considering the following four parameters:

- spanwise distribution of chord length
- spanwise distribution of twist
- shaft speed
- pitch schedule as a function of below-rated wind speed

Given the nearly limitless combinations of these four parameters (particularly the pitch schedule) that could be developed, we initially investigated applying Design of Experiment methods or and Taguchi methods to narrow the matrix of cases to be considered. These efforts proved less than fruitful. In the end we applied a rather brute force approach and simply crunched the numbers for a very large array of cases and picked out the one that provided the best performance.

Figure 11 shows an end view of the final blade design cross sections. A rectangular section has been added at the root. Figure 12 shows the dimensions of the blade, while Figure 13 shows an oblique rendering of the aerodynamic contour.

Figure 11. End view of WEI6K Rotor Cross-Sections

Figure 12. Blade Planform Dimensions

Figure 13. WEI6K Rotor Blade Contour

5.2. Structural Design and Analysis

The baseline blade for the WEI6K turbine features a carbon-glass hybrid construction. The design drivers for the blade design are:

- Tip deflection under maximum load of less than 150 mm
- Axial strain in the carbon fibers of less than 3000 μ strain
- Fatigue life of greater than 20 years

Recent motivation for using carbon in wind turbine rotor blades has primarily been to reduce the weight – and possibly the cost – of very large blades for multi-megawatt wind turbines. Most analyses showed that carbon was not cost effective except for blades in excess of 40 m length. This begs the question of why a designer would consider carbon in a 3m blade. The reason is that material costs are only a small fraction of the cost of a small blade, such that if carbon offers some performance advantage, the increase in cost associated with using carbon might have a negligible impact on the overall blade cost that is outweighed by the benefit of using carbon. We identify two advantages to using carbon in the present turbine:

- reducing the blade weight: while the 3.2m blades designed here are extremely lightweight, the centrifugal forces that they can exert on the blade pitch system are relatively large, given the turbine shaft speed of 150 rpm. Reducing blade weight reduces the loads on the pitch system, allowing the use of smaller components.
- enabling very stiff blade designs: this is related to the first point. The dynamics simulations suggest that at least initially while debugging the pitch system, we would be wise to employ very stiff blades. The weight of such blades in all-glass is prohibitive.

The ultimate and fatigue damage equivalent loads for the design of this blade are taken from Chapter 2. The materials and properties used in the design of the blade are summarized in Table 10. All materials are actual materials currently being used by WEI6K in its blade fabrication development project, and all properties are the result of materials coupon testing. Tip deflection constraint ensured that the strain levels remained well below allowable levels. The structural optimization is an exercise in minimizing the amount of carbon material while maintaining the tip deflection.

The blade is fabricated in six pieces:

- Upper and lower shells are vacuum-infused in female molds and split along the leading and trailing edges.
- Inboard and outboard shear webs are C-spars vacuum-infused on mandrels.
- Leading and trailing edge bond strips are vacuum-infused in female molds.

During assembly, the shear webs and bond strips are bonded into the lower shell, and then the upper shell is bonded to these surfaces. The root is then wrapped with additional reinforcement.

The primary load-carrying member is a 4" wide unidirectional carbon spar cap that runs from root to tip down the center of each shell. It consists of six layers of carbon, each nominally 0.5 mm thick, at the root, tapering the numbers of layers towards the tip. The ply drops all occur towards the inside of the blade, such that no carbon fibers have to pass over a ply drop underneath. The spar cap is sandwiched between two layers of double bias (± 45) E-glass fabric that cover the entire blade shell. Additional layers of glass and carbon cover the surface in the root region. Vinyl foam core is placed aft of the spar cap to improve buckling resistance. Table 11 summarizes the breakdown of material weights in the blade. The total blade weight is approximately 15 lb each.

Table 10. Summary of Key Material Properties Employed in the Present Design

Property	Symbol	Units	E-Glass Fiber/ Epoxy Composite		Carbon Fiber/ Epoxy Composite	
			Test Data	With Combined Safety Factors	Test Data	With Combined Safety Factors
Fiber Orientation	—	—	$\pm 45^\circ$	—	0°	—
Fiber Volume Fraction	v_f	—	52%	—	55%	—
Composite Density	ρ	g/cc	1.85	—	1.45	—
Tensile Modulus	E_{11}	GPa	11.10	—	119.30	—
Transverse Modulus	E_{12}	GPa	11.10	—	8.75	—
Shear Modulus	G_{12}	GPa	12.60	—	5.07	—
Ultimate Axial Strain	ϵ_1^{cu}	—	>5%	—	0.97%	0.40%
Ultimate Axial Stress	F_{11}^u	MPa	155.8	64.9	1160	475
Ult. In-Plane Shear Stress	F_{12}^u	MPa	138.80	57.8	73.62	30.0
Fatigue Strength, $N=1.32 \cdot 10^9$	$\Delta\sigma$	MPa	—	—	185	77
Fatigue Strain Allowable	$\Delta\epsilon$	μstrain	—	—	1555	660

Table 11. Summary of Material Weights in the WEI6K Blade

	Totals	Carbon UD Composite	Glass Biax Composite	Glass 0/90 Composite	Foam	Bonding Compound
Shells	12.06	5.38	5.96	0.58	0.14	
Shear Web	1.33		1.18	0.00	0.15	
Bonding Compound	0.39					0.39
Root Wrap	0.90	0.57	0.33			
Outside edge tape	0.11		0.07	0.05		
Total	14.80	5.95	7.55	0.62	0.29	0.39
Fiber	9.57	3.70	5.30	0.44	0.13	
Resin	5.23	2.26	2.24	0.18	0.16	0.39

Note: All weights are in pounds.

A finite element model of the blade was built in ANSYS 10.0. This model is shown in Figure 15. The blade was modeled almost entirely with SHELL99 8-node layered shell elements. For the upper and lower shells, the nodes were offset to the blade surface, with the wall thickness built up inward. For the shear web, the nodes were placed at the midsurface of the web. The trailing edge bonding compound was represented by a single row of SOLID95 20-node brick elements. The laminate schedule of the blades was modeled in the shell elements via definition of real constant sets representing the regions of differing laminate schedule. The regions of different real constants can be seen in the varying colors in Figure 15. The static load distribution was modeled in the finite element model by applying an equivalent pressure distribution to the spar cap elements, as shown by the blue arrows in Figure 15. The resultant deflection profile is illustrated in Figure 16, from which it can be seen that the peak tip deflection is 144 mm, very near the design target of 150 mm and the FAST result of 149 mm.

Figure 14. Spanwise Mass Distribution of the WEI6K Blade

Figure 15. Finite Element Model of the WEI6K Blade in ANSYS 10

DISPLACEMENT
STEP=1
SUB =1
TIME=1
DMX =143.573

Figure 16. Deflection Profile of the WEI6K Blade Under Maximum Static Loading

Figure 17 illustrates the key component of strain in the carbon layers corresponding to the ultimate static load. It can be seen that significant margins of safety exist with respect to the design allowables. A linear buckling analysis was conducted using the same ultimate static load distribution. The buckling mode shape and load factor of 2.5 are illustrated in Figure 18.

Figure 17. Axial Strain in the Unidirectional Carbon Fibers

For preliminary design purposes, we conducted a simplified fatigue analysis by calculating the fatigue damage equivalent load distribution and applying that to the blade in the same manner as the static load was applied. The only material for which we have fatigue properties is the unidi-

rectional carbon, and so the only components of fatigue damage equivalent stress and strain we examined are the axial components in the unidirectional carbon. These results are illustrated in Figure 19. These values are based upon a reference number of cycles of $1.3 \cdot 10^9$, the full-life number of cycles for the turbine. The fatigue damage equivalent strain never exceeds $182 \mu\text{strain}$, a value corresponding to infinite life.

A modal analysis was conducted in ANSYS using the same model. The first six mode shapes and natural frequencies are shown in Figure 20. This analysis verifies that the rotor blades are stiff. Even the first flap frequency at 11.8 Hz approaches five times the 1P frequency of 2.5 Hz and is in excess of the blade passing frequency of 7.5 Hz.

Figure 18. Eigenbuckling Mode Shape and Load Factor

Figure 19. Fatigue Damage Equivalent Strain in the Carbon Spar Cap

ANSYS DISPLACEMENT
STEP=1
SUB =1
FREQ=11.793771
PowerGraphics
EFACET=1
AVRES=Mat
DMX =44.970835

(a) First Flap, $f=11.8$ Hz

ANSYS DISPLACEMENT
STEP=1
SUB =2
FREQ=21.047769
PowerGraphics
EFACET=1
AVRES=Mat
DMX =37.249773

(b) First Edge, $f=21.0$ Hz

ANSYS DISPLACEMENT
STEP=1
SUB =3
FREQ=39.036567
PowerGraphics
EFACET=1
AVRES=Mat
DMX =60.621185

(c) Second Flap, $f=39.0$ Hz

ANSYS DISPLACEMENT
STEP=1
SUB =4
FREQ=81.227833
PowerGraphics
EFACET=1
AVRES=Mat
DMX =66.350452

(d) Third Flap, $f=21.0$ Hz

ANSYS DISPLACEMENT
STEP=1
SUB =5
FREQ=89.808713
PowerGraphics
EFACET=1
AVRES=Mat
DMX =47.425216

(e) Second Edge, $f=89.8$ Hz

ANSYS DISPLACEMENT
STEP=1
SUB =6
FREQ=109.601
PowerGraphics
EFACET=1
AVRES=Mat
DMX =47.695379

(f) First Torsion, $f=110$ Hz

Figure 20. Blade Dynamic Mode Shapes and Natural Frequencies

6. Control System

The WEI6K turbine will employ an electronic control system that will monitor the turbine operation and adjust electronic and mechanical systems to regulate that operation to ensure maximum safe performance. One of the key distinguishing features of the WEI6K turbine has been, from the outset of the design, the use of active blade pitch control, and a substantial portion of this chapter is dedicated to describing how the pitch control is presently designed.

As presently designed, pitch control serves the following functions:

- Regulation of shaft speed to aid synchronization of the generator during grid connection
- Regulation of power at rated during operation in winds above rated wind speed
- Aerodynamic braking of the rotor during fault conditions

The pitch control system is presently designed only to effect collective pitch – that is, all three blades are nominally driven to the same pitch setting. However, as noted in Chapter 3, each blade has its own drive, and so it will be possible in the future to implement independent control of the pitch of each blade. With the proper input, such independent control can be used to respond to asymmetric loading of the rotor produced by yawed inflow and wind shear across the rotor face. Such functionality is not presently implemented.

The control and protection system for the WEI6K will consist of a programmable logic controller (PLC) that implements the control logic of the system, combined with a small number of sensors that will feed the logic controller key information about the status of the system.

The control system as presently designed will monitor the following inputs:

- Wind Speed
- Wind Direction
- Shaft Speed
- Generator current and voltage
- Grid Availability (bus voltage)
- Pitch position of each blade
- Yaw position
- Pitch servo current and voltage for each blade
- Yaw Motor current and voltage
- Battery charging current
- Battery life
- Generator winding temperature
- Electronics package temperature
- Servo winding temperatures

Fault conditions would include:

- Loss of grid
- Shaft Overspeed
- Generator exceeding max power
- Yaw position not responding to yaw command

- One blade not responding to pitch command
- More than one blade not responding to pitch command
- Excessive pitch motor current
- Excessive yaw motor current
- low battery charge (no pitch in the event of loss of grid)
- Inadequate battery life (risk of battery failure)
- Excessive cable wrap

There are seven different modes of operation presently recognized by the control logic:

1. Generating power (grid-connected and synchronized), which consists of two sub-modes:
 - a. generating and fixed yaw
 - b. generating and yawing
2. Startup and synchronization
3. Normal Shut-down
4. Emergency Shut-down
 - a. pitch-only
 - b. emergency brake
5. Parked and waiting for startup (wind above cut-out or below cut-in)
6. Parked and off-line due to uncorrected fault
7. Cable unwrap

In Mode 7 the number of yaw cycles will be monitored, and when the number of cycles in one direction exceeds a maximum (Excessive cable wrap fault condition), then turbine will implement a normal shut-down and then yaw “backwards” to unwrap the cables. Then the turbine will return to normal operation.

Very little needs to be said about Modes 5 and 6. In Mode 6, the generator is disconnected from the grid, the blades are pitched to feather, and the brake is set to prevent turning of the shaft. The system will remain this way until the fault condition is cleared, either automatically or manually, depending on the nature of the fault.

In Mode 5, the turbine monitors the wind speed to determine if it has risen above cut-in or dropped below cut-out (as the case may be) for a sufficient time to justify reconnecting. The exact threshold by which the wind speed should be inside the operating wind speed band and the duration that this must occur before a reconnect is attempted remains to be determined. We obviously wish to avoid setting the thresholds in such a way that the turbine is continually connecting and disconnecting.

We are considering letting the turbine idle for some period of time when the wind speed is below cut-in, with the blade pitch set so as to allow the rotor to spin at whatever the maximum rate is that it can attain. Under these conditions, if the rotor speed manages to reach the synchronous speed of 150 rpm, then the controller would automatically switch over to Mode 2. This method of operation requires further consideration, and if implemented, this would need to be distinguished as a separate mode from Mode 5 when winds are above cut-out wind speed.

Mode 3 normal shut-down procedure consists of pitching the blades to feather, bringing the rotor to a halt. The generator would be disconnected after power drops to zero. Under some conditions, the parking brake would then be applied. Reasons that the turbine might enter normal shut-down would include:

- mean power dropping to zero for an extended period, the duration of which remains to be defined;
- pitch exceeding the maximum operating pitch for an extended period of time, indicating that wind speed has exceeded cut-out;
- most fault conditions except as noted for Modes 4 and 7 below, and
- normal manual shut-down, such as for maintenance.

Mode 4 emergency shut-down would consist of immediate disconnection of the generator from the grid and simultaneously applying the emergency (parking) brake and – if possible -- pitching of the blades (as available) to feather. The parking brake would remain set after shut-down. Conditions resulting in emergency shut-down would include several fault conditions:

- Loss of grid
- Shaft Overspeed
- Generator exceeding max power
- More than one blade not responding to pitch command
- Low battery charge (no pitch in the event of loss of grid)
- Inadequate battery life (risk of battery failure)

Regarding Modes 1 and 2, prior to synchronization with the grid, it is desirable to hold the shaft speed of the machine as near to the synchronous speed of 150 rpm as possible in order to minimize synchronization transients. Therefore, prior to synchronization the blade pitch controller operates in speed regulation mode, and attempts to hold the rotor speed at a constant 150 rpm. The blades must initially be pitched to a condition that provides for positive torque in order to allow for acceleration of the rotor during startup, but since there is no load on the system under these conditions, as the shaft speed approaches 150 rpm, the blades must be pitched to a condition that essentially maintains zero torque in order to avoid further acceleration. The primary challenge is holding the speed constant and synchronizing in the presence of gusting inflow conditions.

In the synchronous power generation mode, the pitch controller attempts to maximize power production when the wind speed is above the cut in value and below the rated value. And it attempts to limit the power production to the rated 6 kW value when the wind speed is above the rated value, 9 m/s.

Using FAST, we have conducted extensive simulations of the normal operation of the WEI6K turbine under conditions of steady in-flow, IEC-prescribed design load conditions, and during turbulent conditions. Details of these simulations are documented in Chapter 2. These simulations depended upon proper implement of a pitch controller in FAST. For Mode 1 (Normal) Operation, the WEI6K employs a pitch rate controller. The control scheme is PI (Proportional Integral), operating on the error defined as the difference between rated power (6 kW) and the generator power. This controller was tuned by subjecting the FAST model to step changes in inflow velocity, starting at 9 m/s and continuing to 25 m/s in 1 m/s intervals. The response of the pitch

system to these step function inputs was observed. The magnitude of the proportional gain was increased until undamped oscillatory behavior was observed when the wind speed was increased from 9 to 10 m/s. The standard Ziegler-Nichols method for tuning closed loop controllers calls for dividing this value of proportional gain by 2.2 to obtain the optimal value to employ. The proportional gain had to be reduced at higher wind speeds due to the increased sensitivity of the system to pitch as the pitch angle increases. The Ziegler-Nichols method failed in allowing us to develop an optimal value of the integral time constant, τ_i . This method suggests observing the frequency of undamped oscillations and setting τ_i equal to approximately 80% of the period of those oscillations. However, in our simulations, the oscillations occurred at the shaft frequency due to physical influences, and this distorted the result. Therefore, we adjusted τ_i until we obtained a desirable response.

This PI controller was implemented into FAST 5.1 through a custom FORTRAN module replacing the sample pitch control module compiled with the standard package. Several minor modifications to core FAST routines were implemented in order to feed additional information to the controller. These changes are described in Chapter 2. Because of the initial simplicity of the PI controller, the control strategy was initially implemented in the time domain.

Our examination of several pitch control models for other wind turbines revealed that most of them contain only a model of the frequency response of the drive system. Modeling the servo response alone, however, neglects several other influences on the response of the pitch system, including the aerodynamic pitch loads, the inertial loads of the blade, and the pitch bearing friction loads. From the outset, the blade inertial loads were determined to be completely negligible. However, it was not initially clear that both the aerodynamic loads and the friction are non-negligible influences for the present turbine. They are also nonlinear influences that cannot be easily implemented as a frequency response, as can the servo response. The only manner in which these three influences (servo inertia, bearing friction, and aerodynamics) could be implemented is in the time domain. At each time step, therefore, we would calculate the loads acting on the system externally, and subtract that from the torque available from the motor, leaving the net torque available from the pitch system. From the net torque and the known inertia of the drive system, we could calculate the acceleration. This approach is rather cumbersome. Fortunately, subsequent analysis with FAST/SimuLink determined that the bearing friction and blade aerodynamic pitching torque could also be neglected in comparison to the drive inertia, and so this approach was not implemented.

Figure 21 illustrates the typical response of the present pitch system to an extreme operating gust during operation in steady winds at rated wind speed, as modeled in FAST 5.1. Figure 22 illustrates the response to normal turbulence imposed on top of an extreme gust.

Figure 21. FAST 5.1 Simulation of Operation During IEC Extreme Operating Gust at a $V_r=9$ m/s

Figure 22. FAST 5.1 Simulation of Operation During Normal IEC Class IIA Turbulence at a Mean Wind Speed of 8 m/s transitioning to 16 m/s

7. Tower Design

Wetzel Engineering proposed that the WEI6K turbine would be offered with a tilt-up free-standing monopole tower. Valmont Wind Energy initially designed the 100' free-standing steel monopole tower shown in Figure 23 and summarized in Table 12 and Table 13. This is not a tilt-up tower. Valmont designed the tower so that the base is simply sunk in to the ground. There is no concrete foundation. The customer would bore a hole in the ground 30" in diameter by 13'6" deep, and using a crane, drop the bottom section of the tower in to the hole and backfill. Then they would use the crane to place the top two sections of the tower in place, and then place the turbine on top. Based on Valmont's experience, they believed that the cost of boring the hole and the cost of the crane would be more than compensated by the savings in costs avoided by this design. These include the cost of the gin pole, grading and pouring a conventional concrete foundation, mounting the base plate, and hoisting the tower. Moreover, the tower top weight significantly exceeds the lateral aerodynamic loads, so if the tower has to be designed as a tilt-up, then it will have to be designed to accommodate the weight of the turbine cantilevered during tilt-up. Otherwise, the customer will still have to rent a crane in order to place the turbine on top, which somewhat defeats the point of the tilt-up concept.

At the time nearly three years ago that this tower was quoted, the price was considered very competitive. Unfortunately, the recent severe escalation in steel prices has nearly doubled the cost of this tower at the present time. The cost could rise further in the future if steel costs continue to climb. As a result, Valmont declined to quote a version of this tower that could be tilted up with the turbine in place. They believe that they could not produce a cost-effective design for a such a tower in a free-standing monopole configuration.

As an alternative, Valmont did quote an off-the-shelf 100' guyed lattice tower from their 45V series of standard towers. Although the cost is competitive, we were hoping to avoid guyed towers for aesthetic reasons.

All dynamic simulations for loads and performance analysis have been conducted using the free-standing monopole tower. However, in the cost of energy analyses reported in Chapter 1, we do consider both towers. We do not believe that the difference in the designs of the two towers will make a substantial difference in the loads estimation. The monopole tower turned out to be relatively stiff, with a maximum tower top displacement of only 12".

ITEM ID	NO. REQD	FEATURES	WEIGHT (LBS)
1	1	SECTION A	2,602
2	1	SECTION B	2,082
3	1	SECTION C	920
4	1	BEARING PLATE	
	1	EXTERIOR COAL TAR 18 MILS (LENGTH = 14.50')	
	1	HAND HOLE (6" x 18") (TUBE)	25
	1	HAND HOLE (6" x 18") (TUBE)	25
	2	GROUND PLATE	1
	1	POLE CAP	21

NOTES:

1. POLE SHAFT-GOVERNING REACTIONS
 MOMENT = 1,359 IN-KIPS
 SHEAR = 962 #
 VERTICAL = 10,709 #

SECTION INFORMATION					
ITEM ID	LENGTH	BASE OD	TOP OD	THK	MATL
1	48' - 0.00"	29.72"	23.60"	0.188"	S-22
2	47' - 9.00"	24.52"	18.43"	0.188"	S-22
3	25' - 9.00"	19.28"	16.00"	0.188"	S-22

Figure 23. Valmont Free-Standing Monopole Tower

Table 12. Valmont Monopole Tower Specification

DESIGN

Deflection limitation of 12.5 inches was used for the design of this pole under the "Ultimate Loads" provided. The deflection limitation design did govern the design and dictated a larger pole than would be required for resisting the loading.

The pole includes galvanized finish, below grade protection for the embedded portion of the pole (plus 1 foot above grade), 2 handholes (1 near ground, other near top), and 2 grounding plate (near groundline and top).

Point of fixity for embedded structures is assumed to be at the ground line.

Our design calculations are based on static loads. Wind induced vibration is believed to be more likely to happen when structures (or components such as arms) are installed without insulators and conductors. It is considered good practice for installers to attach at least some equipment to each arm at the time of installation of the structure.

MATERIAL

The following **materials** will be used:

shaft and attachment plate: (Galvanized)
thk <= 0.5" Valmont S-22 (exceeds ASTM A572, Gr 65, Heat test)

FINISH SPECIFICATIONS

Hot-dip Galvanizing of Members per Valmont Specification F-1 (exceeds ASTM A123).

Corrocote coating meeting Valmont F-398 specification is proposed for the embedded portion of the structure.

Table 13. Summary of Design and Analysis Information

----- DESIGN SUMMARY -----					
ABOVE GROUND HEIGHT (FT)	100.00	GROUND LINE DIAMETER (IN)	28.000	POLE SHAFT WEIGHT (LB)	5603.
EMBEDMENT LENGTH (FT)	13.50	TOP DIAMETER (IN)	16.000		
TOTAL POLE LENGTH (FT)	113.50	POLE TAPER (IN/FT)	0.1275	SHAPE:	12-SIDED SYMMETRICAL POLYGON
CONNECTIONS BETWEEN SECTIONS	/FIRST/	/SECOND/			
HEIGHT ABOVE GROUND (FT)	34.50	78.00			
TYPE	LAP SPLICE	LAP SPLICE			
OVERLAP LENGTH	51"	45"			
SECTION CHARACTERISTICS	/FIRST/	/SECOND/	/THIRD/		
BASE DIAMETER (IN)	29.721	24.515	19.279		
TOP DIAMETER (IN)	23.601	18.430	16.000		
THICKNESS (IN)	0.18750	0.18750	0.18750		
LENGTH	48' 0"	47' 9"	25' 9"		
WEIGHT (LB)	2602.	2082.	920.		
----- ANALYSIS SUMMARY -----					
	GROUND LINE	MAX. STRESS 1ST SECT.	MAX. STRESS 2ND SECT.	MAX. STRESS 3RD SECT.	POLE TOP
GOVERNING LOADING CASE	FACT	FACT	FACT	FACT	TURB
HEIGHT (FT)	0.00	0.00	34.50	78.00	100.00
RESULTANT MOMENT (IN-KIP)	1359.	1359.	923.	349.	39.
SHEAR FORCE (LB)	962.	962.	962.	962.	575.
VERTICAL FORCE (LB)	10709.	10709.	7337.	3968.	1600.
COMBINED STRESS (KSI)	12.48	12.48	11.51	7.15	1.21
ALLOWABLE STRESS (KSI)	57.66	57.66	63.29	65.00	65.00
ALLOWABLE/COMBINED STRESS	4.62	4.62	5.50	9.09	53.65
TOTAL DEFLECTION (IN)	0.00	0.00	2.54	13.22	12.25

NOTE: DIAMETERS ARE OUTSIDE, MEASURED ACROSS THE FLATS

8. Conclusions and Recommendations

The results of the present study show that the WEI6K turbine could generate electricity at a levelized cost of energy (COE) between 7.3 and 8.9 ¢/kWh at an IEC Class II site, with an average wind speed of 8.5 m/s at hub height, depending upon whether the customer uses a guyed truss tower (the lower figure) or a monopole tower. For the NREL Reference Site, with a mean wind speed of 5.35 m/s at 10 m height, the turbine would generate at a levelized cost of energy of between 9.7 and 11.9 ¢/kWh. The lowest of these numbers is presently competitive with retail electricity rates in most of the country. The 8.9 ¢/kWh is still competitive with retail rates in many regions of the country with high electricity costs.

The study further concludes that several design changes could shave 10-14% from the cost of energy determined in the preliminary design. These changes include:

- A new tower design is required that (a) offers tilt-up capability without guy wires and (b) takes advantage of the lowered loads produced by the pitch control. The current monopole design remains rather conservative with regard to the tower top displacement, and it was designed to early loads estimates that were much higher than the final loads. Significant cost savings can be realized in the tower. If a tilt-up monopole tower can be developed for the same price as the guyed tower, then there is no impact on cost, but we believe the machine will be more marketable.
- Select or design a family of airfoils more appropriate for pitch regulation on a turbine of this size. The S822 airfoil has rather restrained lift coefficients intended for well behaved stall regulation. We can increase our energy capture significantly with airfoils with higher maximum lift coefficients.
- Tune the pitch controller properly to minimize shedding of power during operation in the transition from Region 2 to 3.
- Value engineer the pitch system to shave costs, including considering a collective pitch system.
- Refine the design of the hub and main frame castings to minimize weight and cost.

We are generally encouraged by the results. The preliminary numbers show that we can produce a turbine that is competitive with retail electric rates at relatively windy IEC Class II sites. With further improvements in the design, we believe the turbine could be competitive at sites with lesser wind resource.