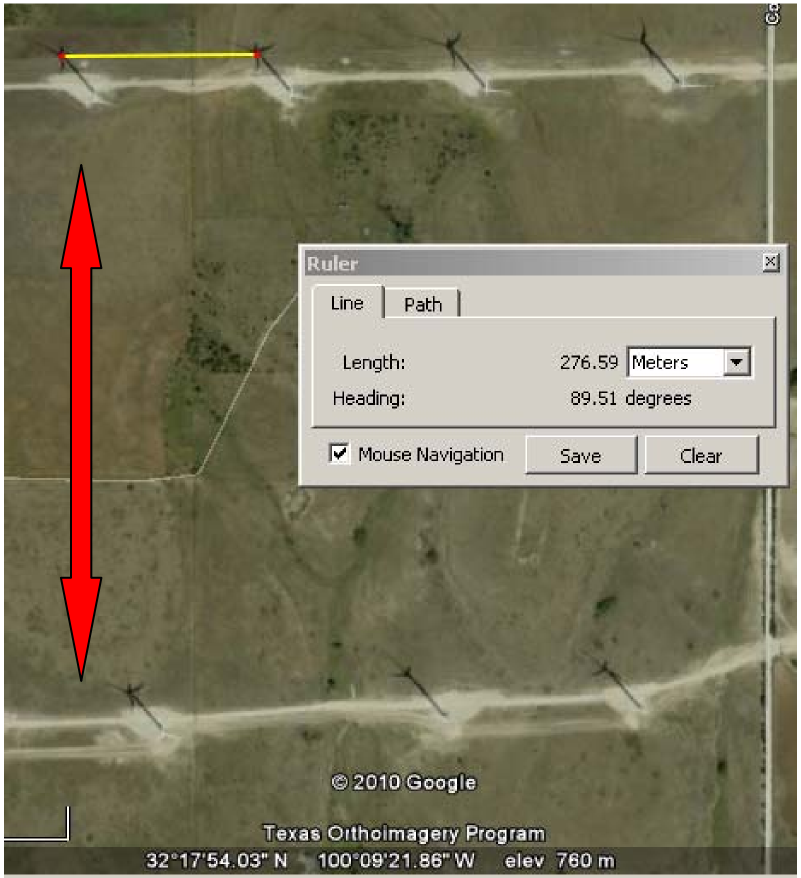
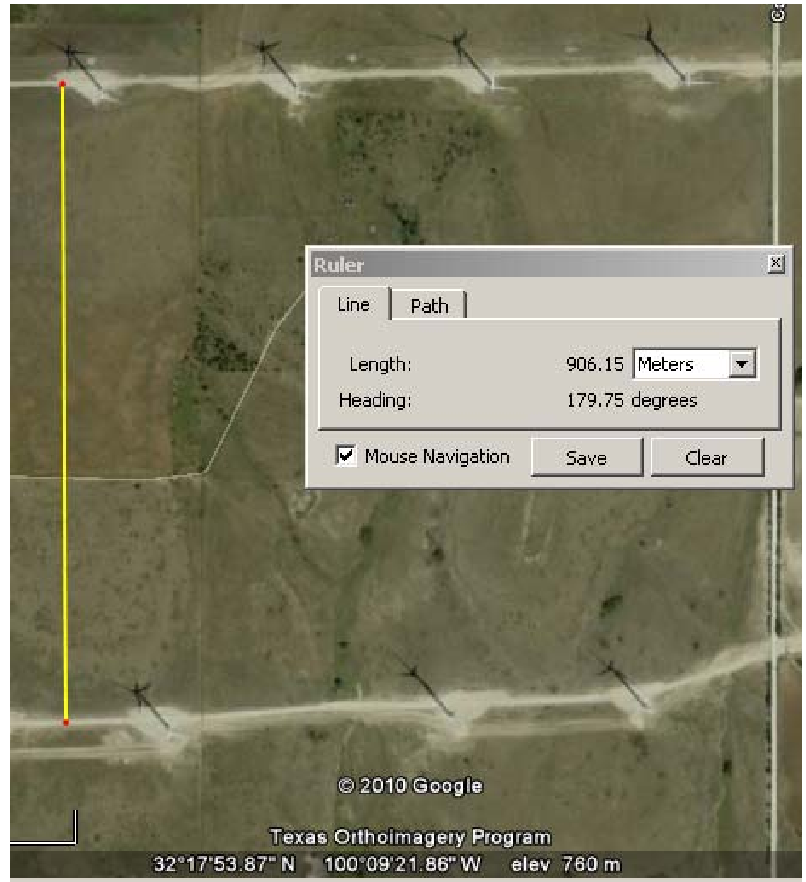
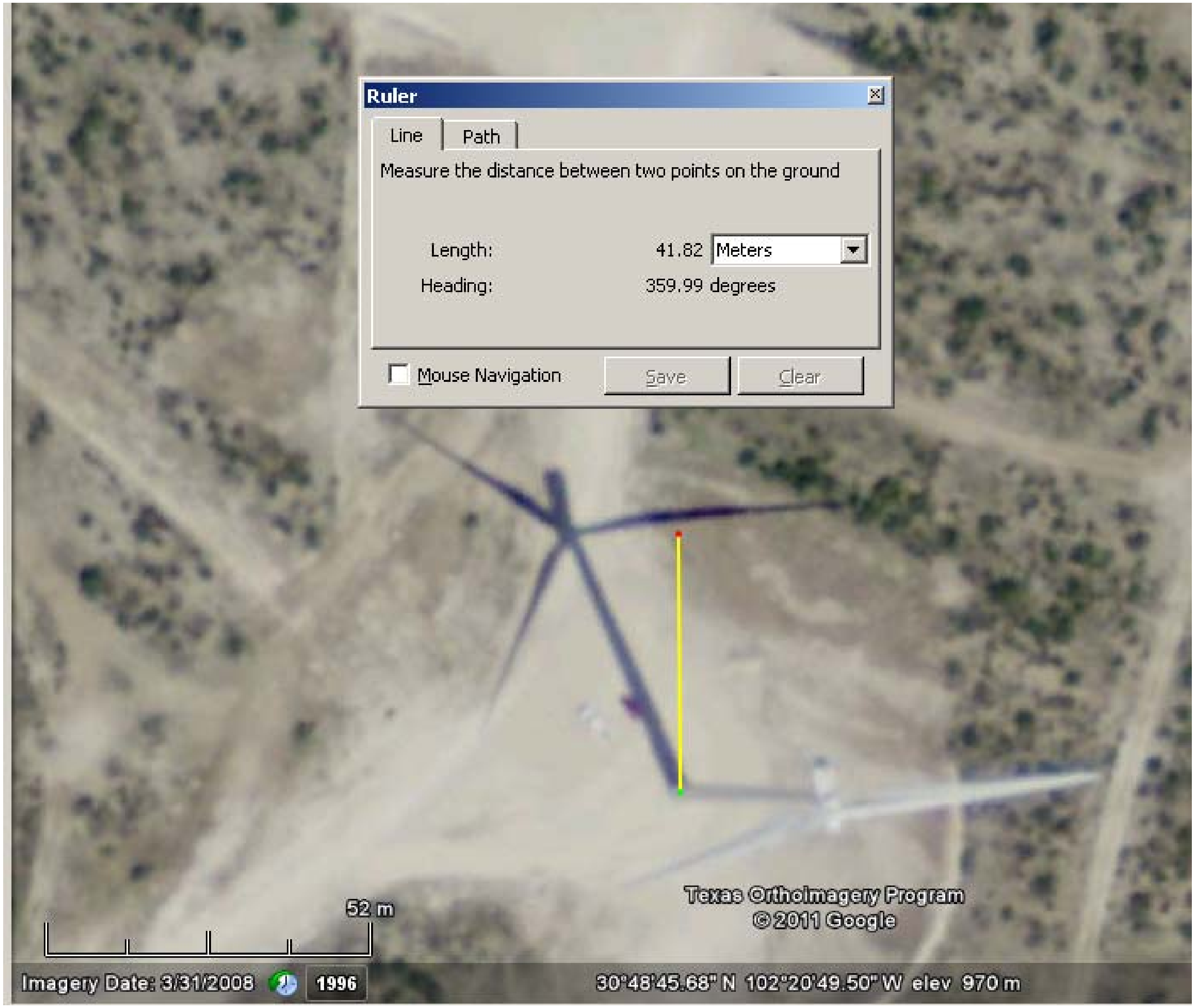
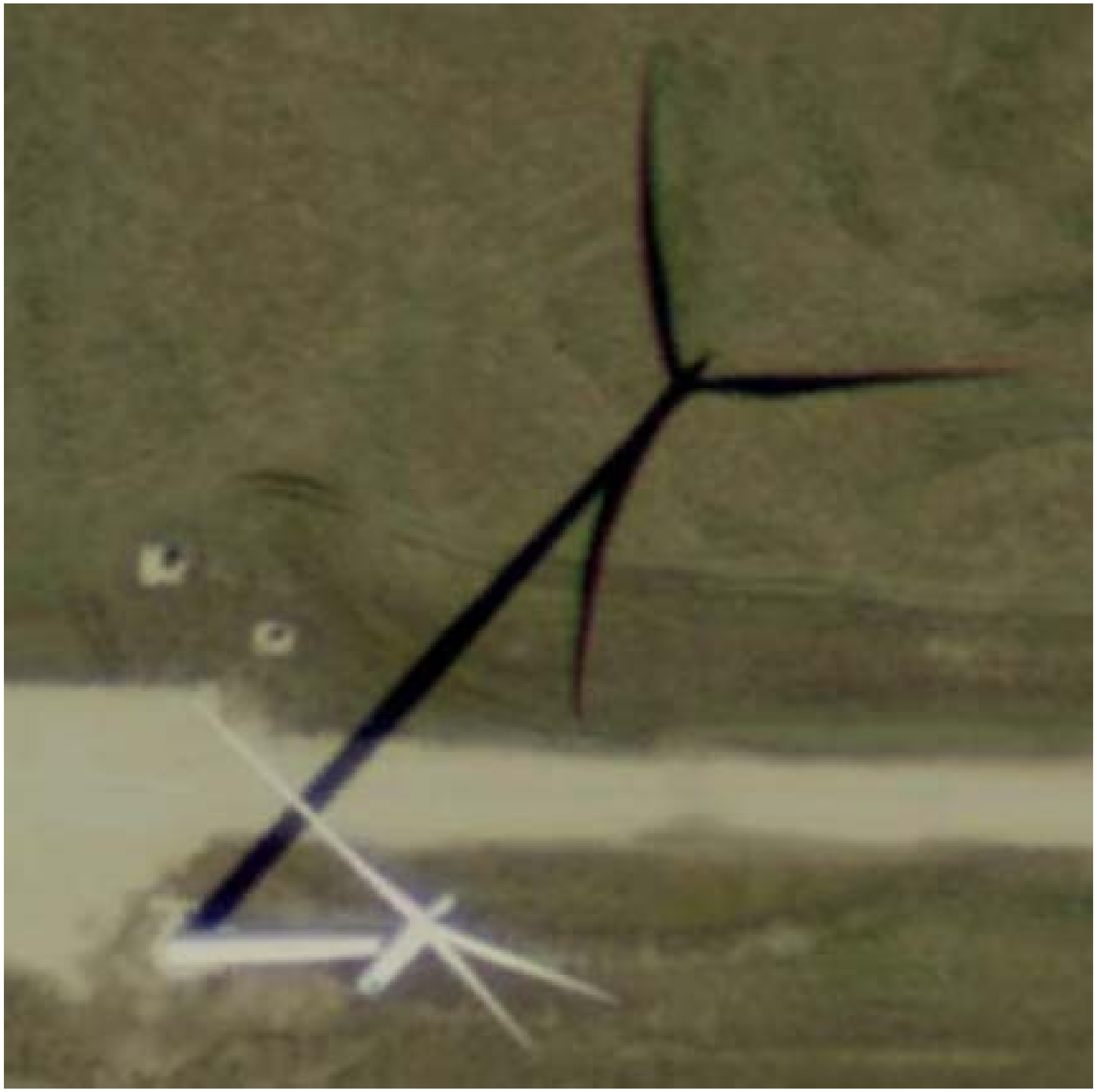




Turbine Spacing. Rows are perpendicular to prevailing wind direction. Turbines are spaced about 3 top heights apart in the rows, with about 10 top heights between rows.

Determine My Time of Day, Hub Height and Swept Area and Manufacturer





Specs	GE 1.5sle	GE 1.5xle	GE 2.5	MB 2.4	Comments
Rated Output - MW	1.5	1.5	2.5	2.4	
Rated Wind Speed - m/s	12.5	11.5	12.5	11.5	
Hub Height - m	65	80	85	80	
Rotor Diameter D - m	77	82.5	100	102	
Swept Area - m^2	4657	5346	7854	8171	
Cut-in Wind Speed - m/s	3.5	3.5	3.0	3.0	
Cut-Out Wind Speed - m/s	25.0	20.0	25.0	25.0	
Rated Blade RPM	20			15	
Blade Length - m				49.7	
Voltage	690			690	
Rated Generator RPM	1200				
Calculations					
Tip Top - m	103.5	121.3	135.0	131.0	
Tip Bottom - m	26.5	38.8	35.0	29.0	
PI * D^2 / 4 - m2	4657	5346	7854	8171	
Tip Speed - m/s	81			80	About 80 m/s
Tip Speed Ratio	6.5			7.0	6 to 7
Wind Power Density (KA=KT=1) at Rated Wind Speed - W/m^2	1196	932	1196	932	About 1 kW/m^2
Wind Power at Rated Wind Speed - MW	5.6	5.0	9.4	7.6	
Rated Output MW / Wind Power at Rated Speed MW	0.27	0.30	0.27	0.32	About 0.3
Wind Speed(tip top) / Wind Speed (tip bottom), for alpha = 1/7th	1.21	1.18	1.21	1.24	
Wind Speed(tip top) / Wind Speed (tip bottom), for alpha = 0.1	1.15	1.12	1.14	1.16	
Wind Pressure(tip top) / Wind Pressure (tip bottom), for alpha = 1/7th	1.46	1.39	1.46	1.54	
Wind Pressure(tip top) / Wind Pressure (tip bottom), for alpha = 0.1	1.32	1.25	1.30	1.35	About 1.5

Other Comments
1. 100 m tip-top gets you 1.5 MW, 150 m tip-top gets you 2.5 MW. So, MW varies approx. by the square of tip-top height.
2. Required footprint per turbine is 3 tip-top heights perpendicular to prevailing wind direction, and 10 tip-tops in the prevailing wind direction
3. Both footprint and MW vary by the square of tip-top height, and the ratio is about 1.5 MW / 300 / 1000 = 1.5 MW / 0.3 km^2, which is about 5 MW per km^2.
4. Conversion factors: 1609 m/mile. 12.5 m/s = 28 mph. 80 m/s = 178 mph.

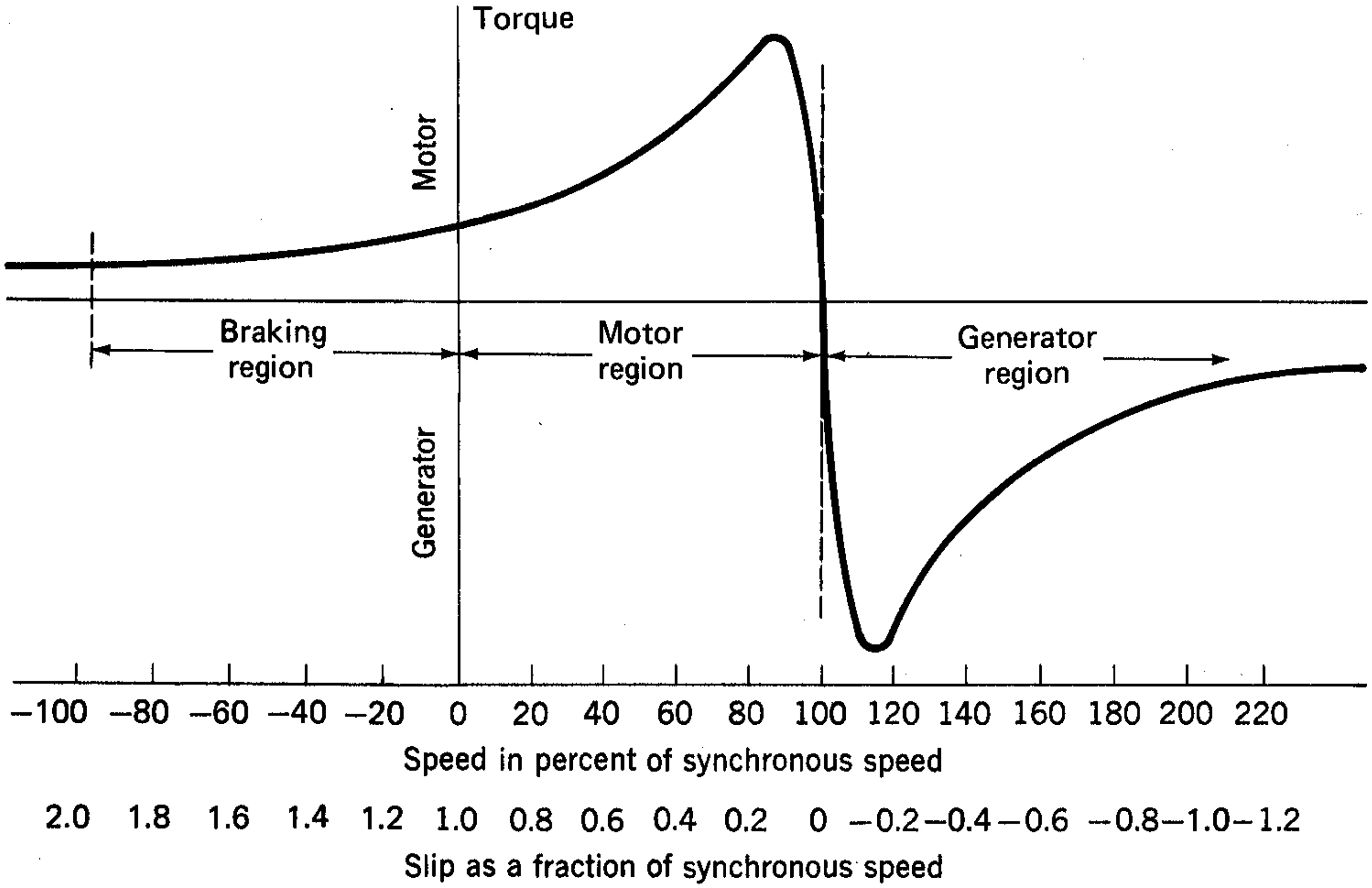


Fig. 9-13. Induction-machine torque-slip curve showing braking, motor, and generator regions.

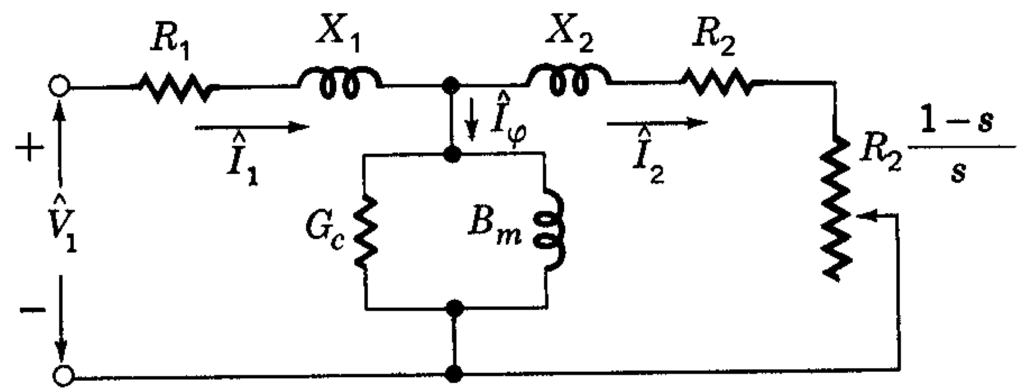


Fig. 9-9. Alternative form of equivalent circuit.

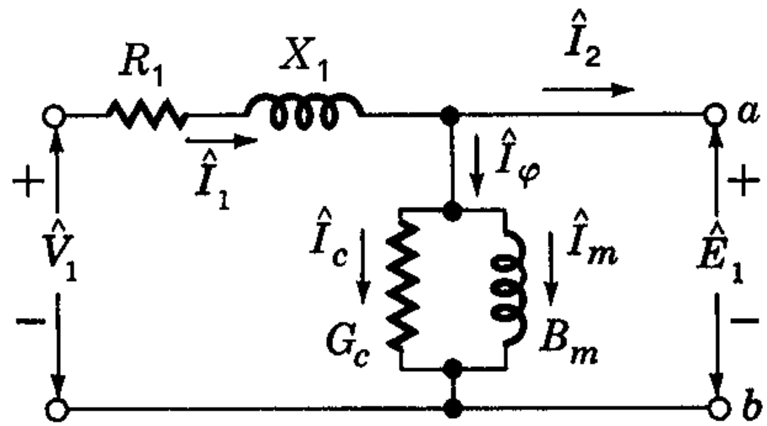
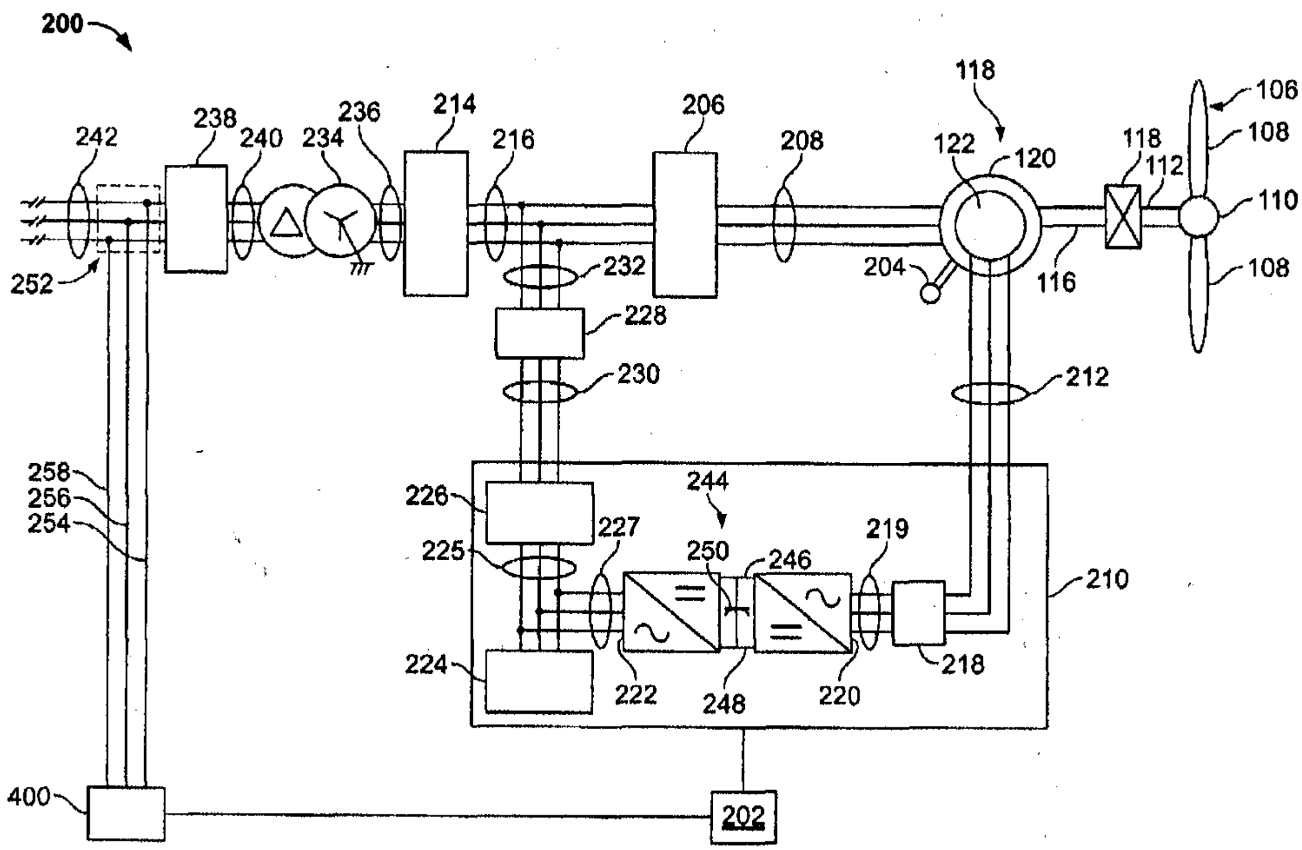
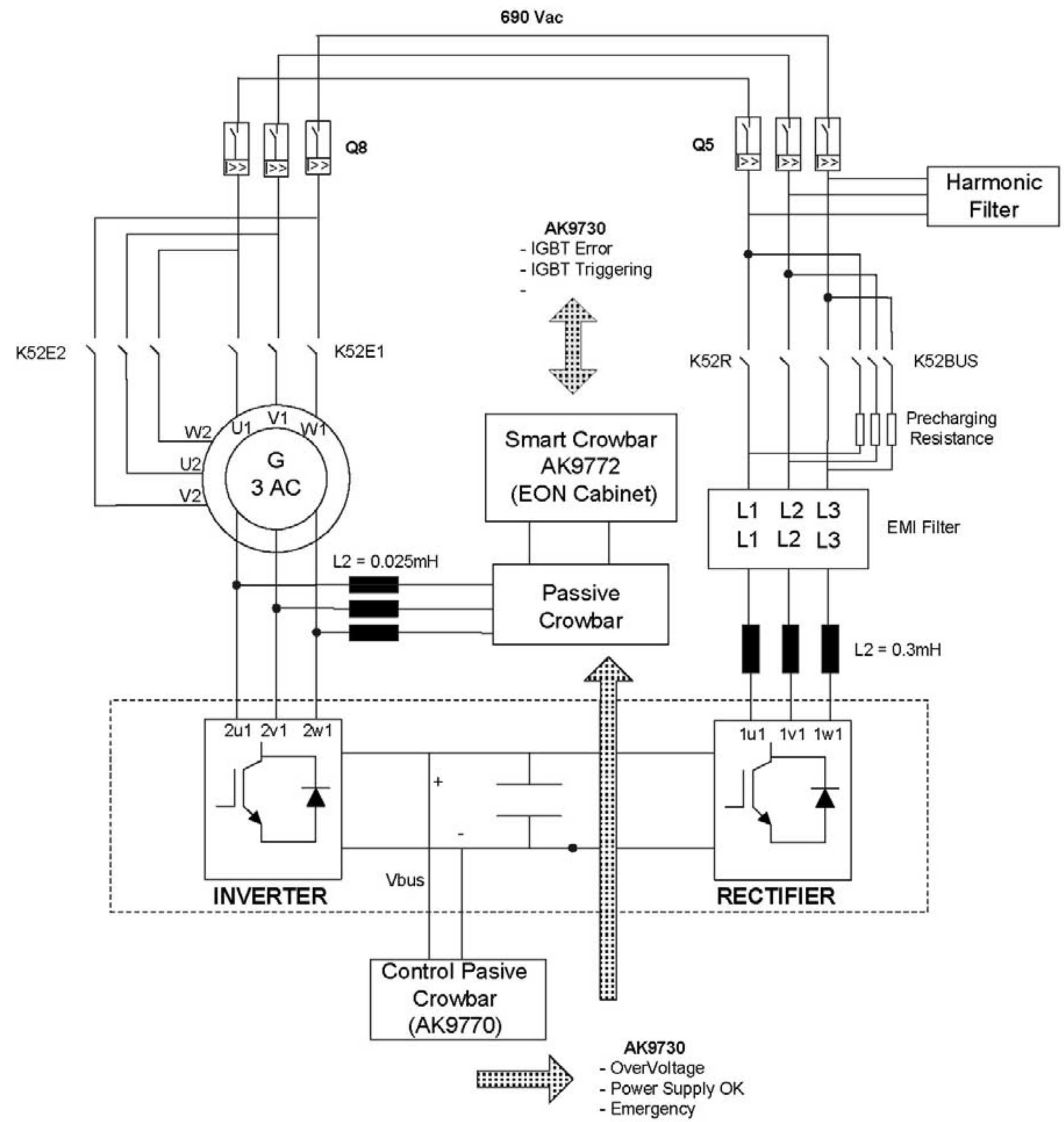
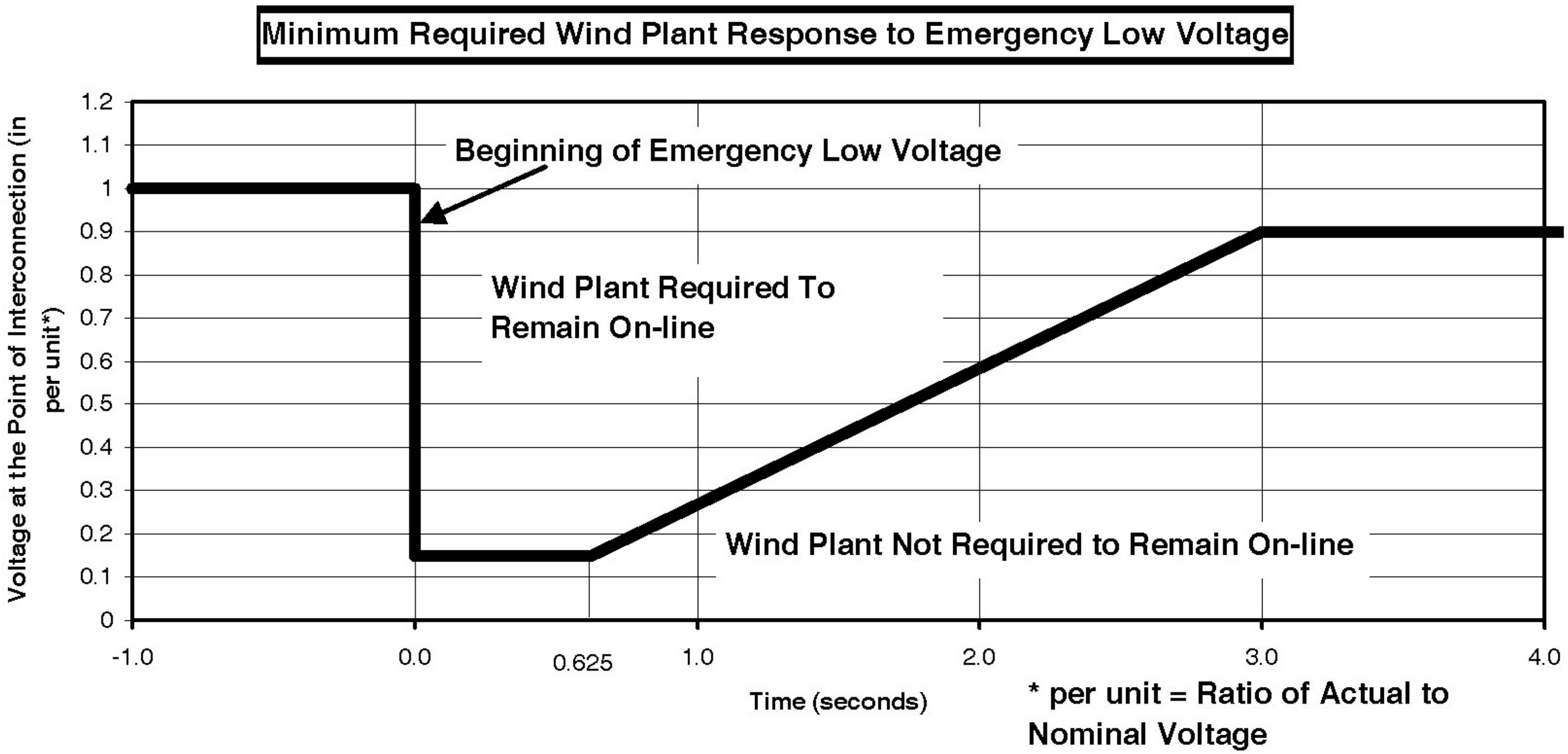


Fig. 9-6. Stator equivalent circuit for a polyphase induction motor.


200
118
106
242
238
240
234
236
214
216
206
208
122
120
118
112
108
110
108
252
232
204
116
228
230
212
258
256
254
226
244
227
219
225
250
246
210
224
222
248
220
218
400
202


690 Vac
Q8
Q5
Harmonic Filter
AK9730
- IGBT Error
- IGBT Triggering
-
K52E2
K52E1
K52R
K52BUS
Precharging Resistance
W2
U1
V1
W1
U2
V2
G
3 AC
Smart Crowbar AK9772 (EON Cabinet)
L1 L2 L3
L1 L2 L3
EMI Filter
L2 = 0.025mH
Passive Crowbar
L2 = 0.3mH
2u1 2v1 2w1
1u1 1v1 1w1
+
-
Vbus
INVERTER
RECTIFIER
Control Pasive Crowbar (AK9770)
AK9730
- OverVoltage
- Power Supply OK
- Emergency

Parameter	Value	Unit
Rated power	1545	KW
Rated voltage	575	V
Apparent Power (@ PF = 0.9 lag)	1717	KVA
Rated frequency	60	Hz
Poles	6	
Power factor - standard	+/- 0.95	
Power factor - optional	+/- 0.90	
Rated current		
Stator (PF = 0.9 lag)	1509	A
Rotor (PF = 0.9 lag)	624	A
Locked rotor voltage	1715	V
Transformation ratio	0.335	
Connection		
Stator	Star or Delta	
Rotor	Star	
Synchronous speed	1200	rpm
Rated speed	1440	rpm
Slip at rated speed	-20	%
Speed range	800 - 1600	rpm
Generator moment of inertia	75	$Kg.m^2$
Generator inertia constant	0.55	s
Total moment of inertia (ref to high speed side)	960	$Kg.m^2$
Total Inertia constant (H)		
at 1200 rpm	4.55	s
at 1440 rpm	6.55	s


Minimum Required Wind Plant Response to Emergency Low Voltage
Beginning of Emergency Low Voltage
Wind Plant Required To
Remain On-line
Wind Plant Not Required to Remain On-line
Voltage at the Point of Interconnection (in per unit*)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-1.0
0.0
0.625
1.0
2.0
3.0
4.0
Time (seconds)
* per unit = Ratio of Actual to Nominal Voltage

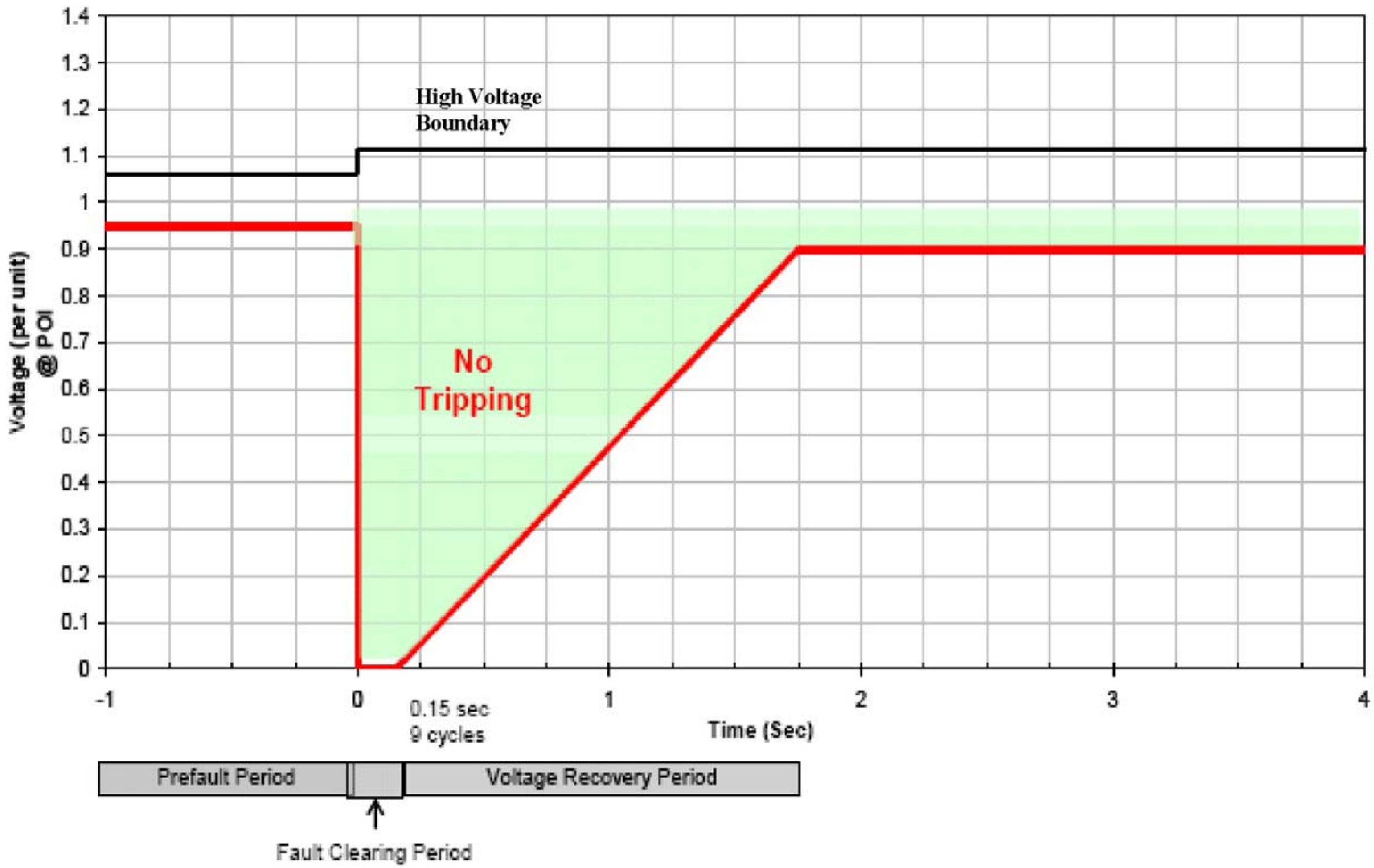
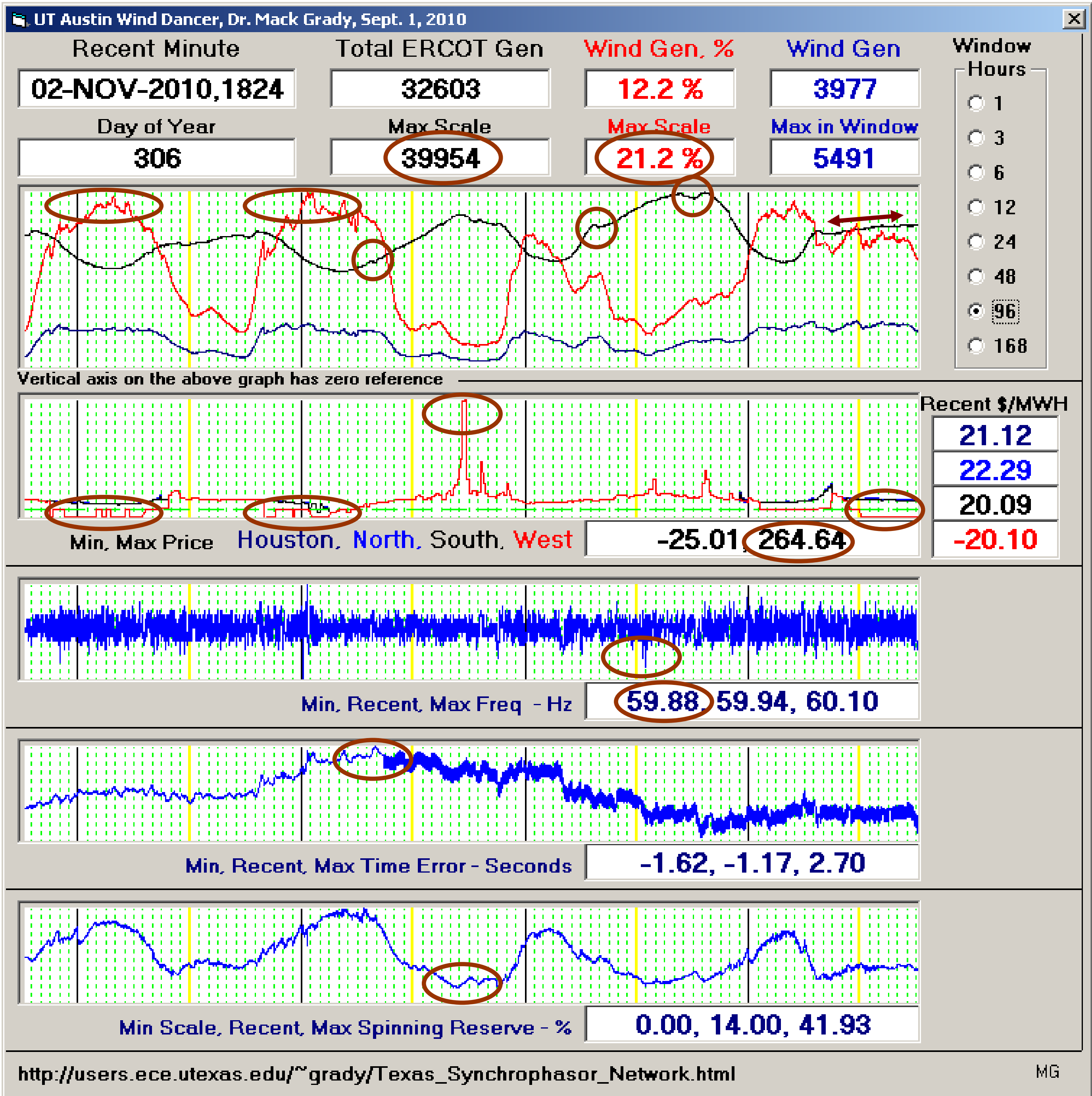


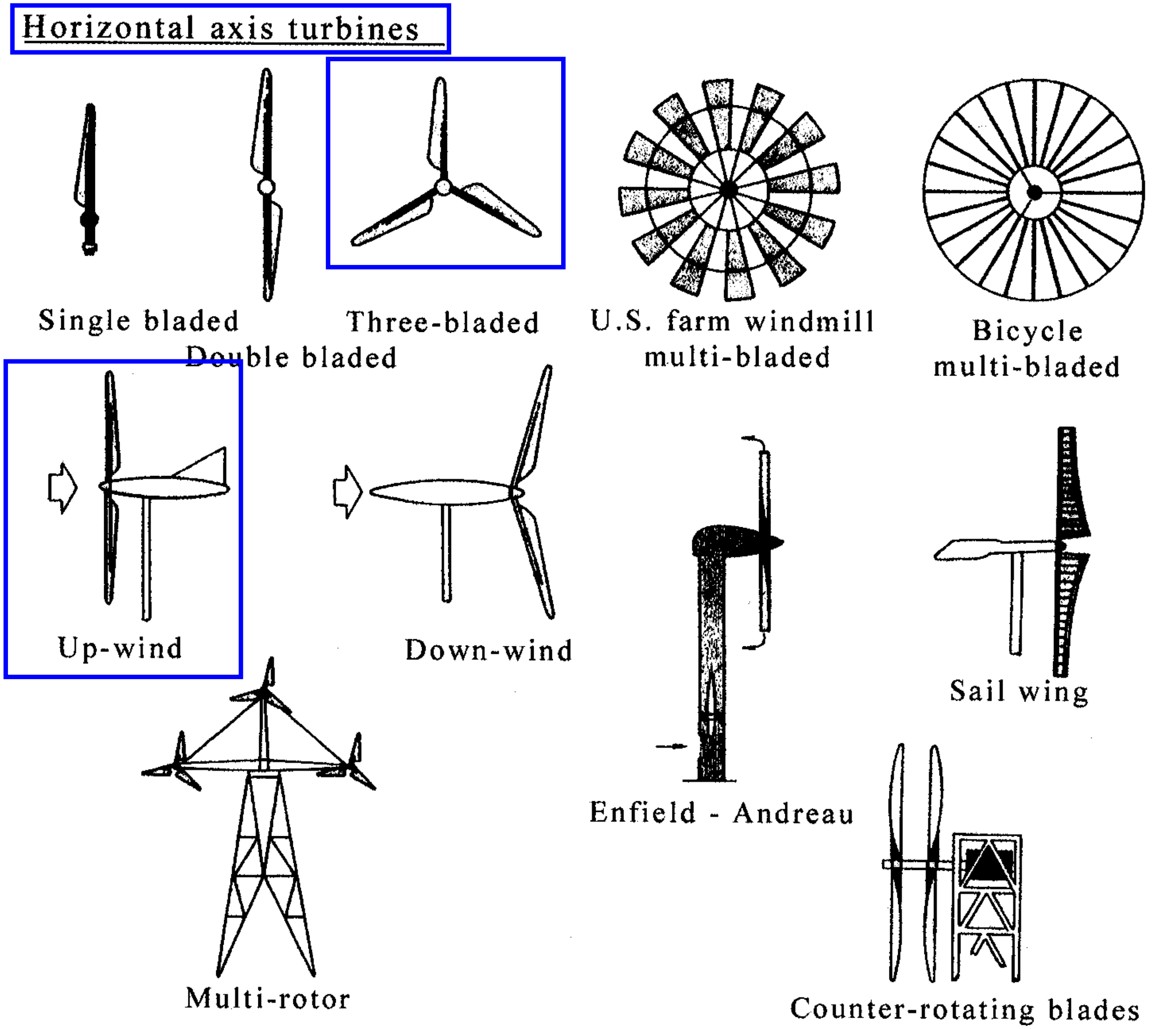
Figure 1: Voltage Ride-Through Boundaries For Wind-powered Generation Resources



Each Annotation Falls Into a Category

- Wind gen artificially held back
- Not enough gen – makes some money
- Significant unit trip
- Winter started
- Rush hour
- Not rush hour
- How big compared to summer peak?
- Wind gen in phase with load
- Clocks approaching correction tolerance limit
- Wind gen too high

Blue font and lines – need to know



These are all lift-type (the sweep surface faces the wind)

These are suitable for utility-scale generation

Too much interference from tower

Not high enough above ground

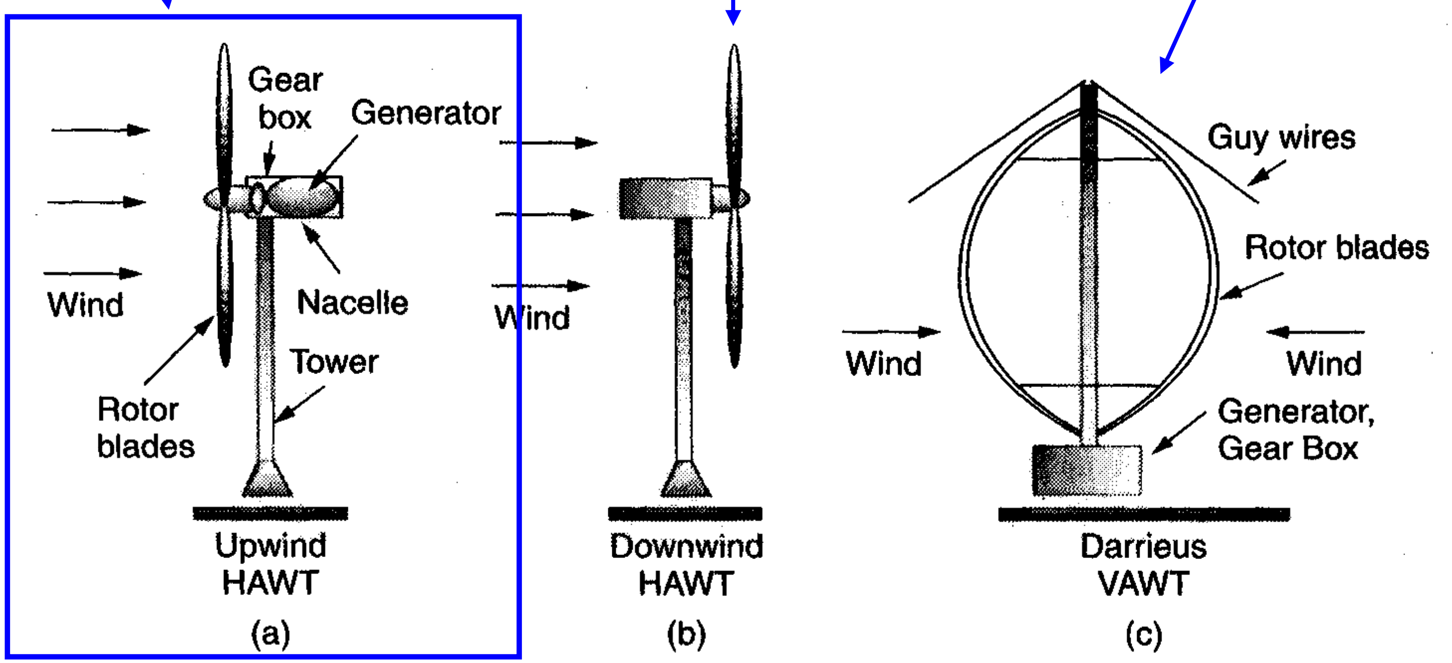
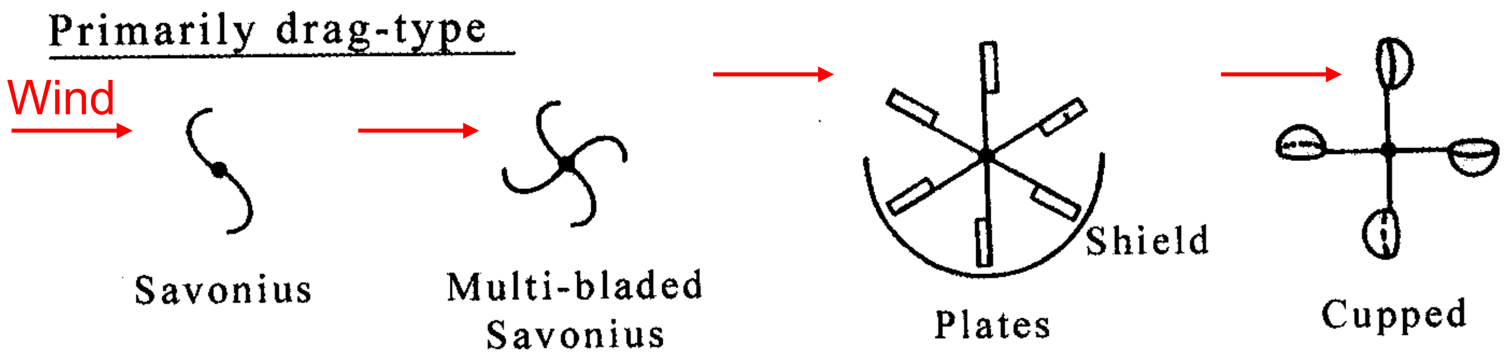


Figure 6.4 Horizontal axis wind turbines (HAWT) are either upwind machines (a) or downwind machines (b). Vertical axis wind turbines (VAWT) accept the wind from any direction (c).

Drag-Type - not suitable for serious power



Windspeed (m/s)	Windspeed (mph)	Power (W/m^2)
0	0	0
1	2.24	1
2	4.47	5
3	6.71	17
4	8.95	39
5	11.19	77
6	13.42	132
7	15.66	210
8	17.90	314
9	20.13	447
10	22.37	613
11	24.61	815
12	26.84	1058
13	29.08	1346
14	31.32	1681
15	33.56	2067

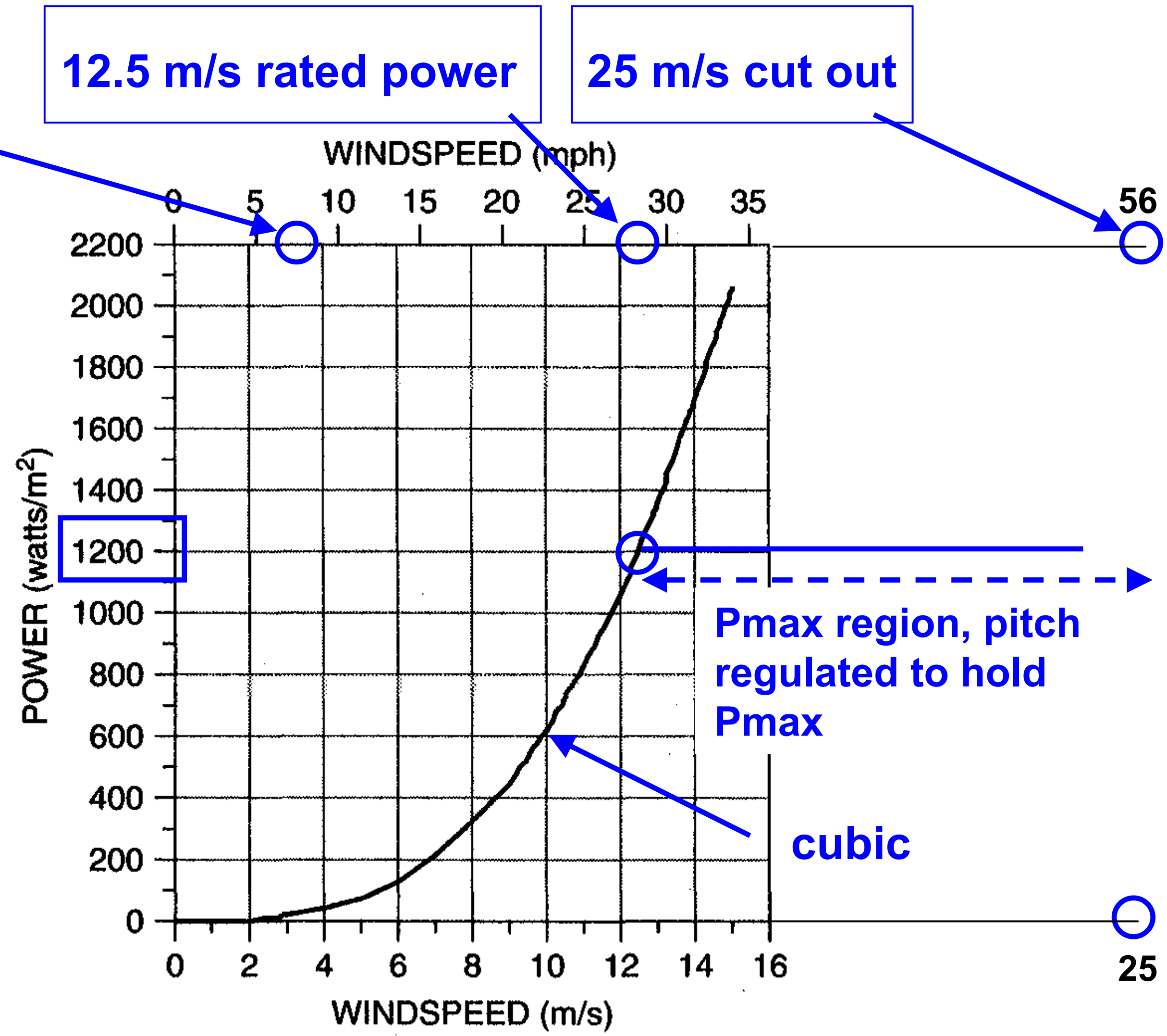
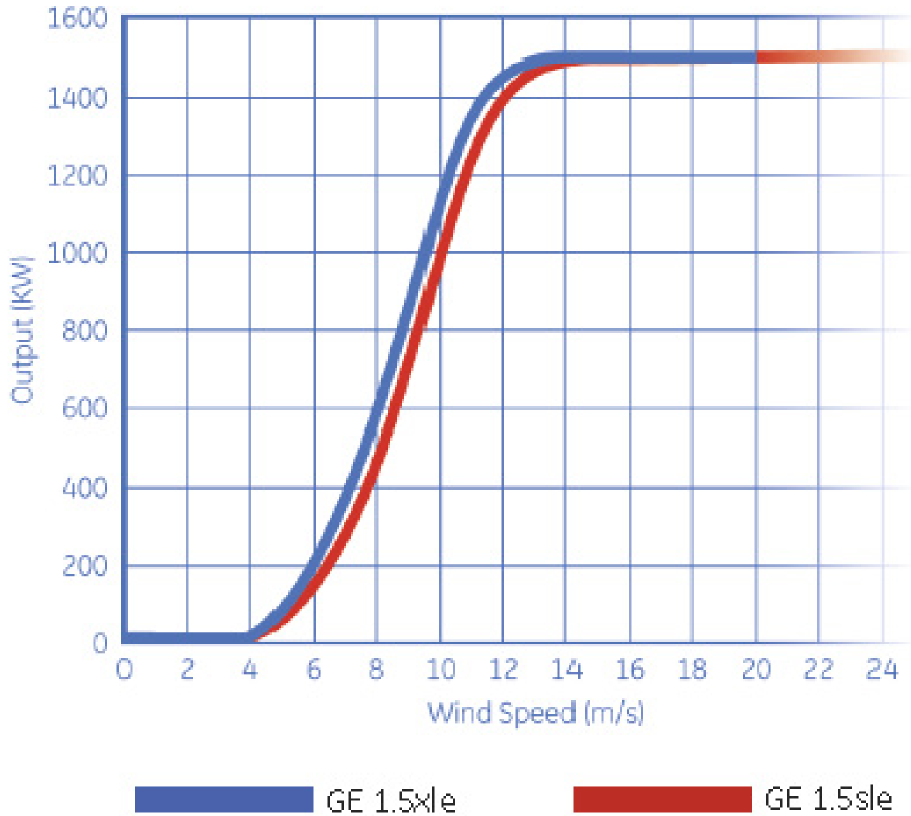


Figure 6.5 Power in the wind, per square meter of cross section, at 15°C and 1 atm.

1 mile = 1609 m

Power Curve



1600
1400
1200
1000
800
600
400
200
0
Output (KW)
0 2 4 6 8 10 12 14 16 18 20 22 24
Wind Speed (m/s)
GE 1.5xle
GE 1.5sle

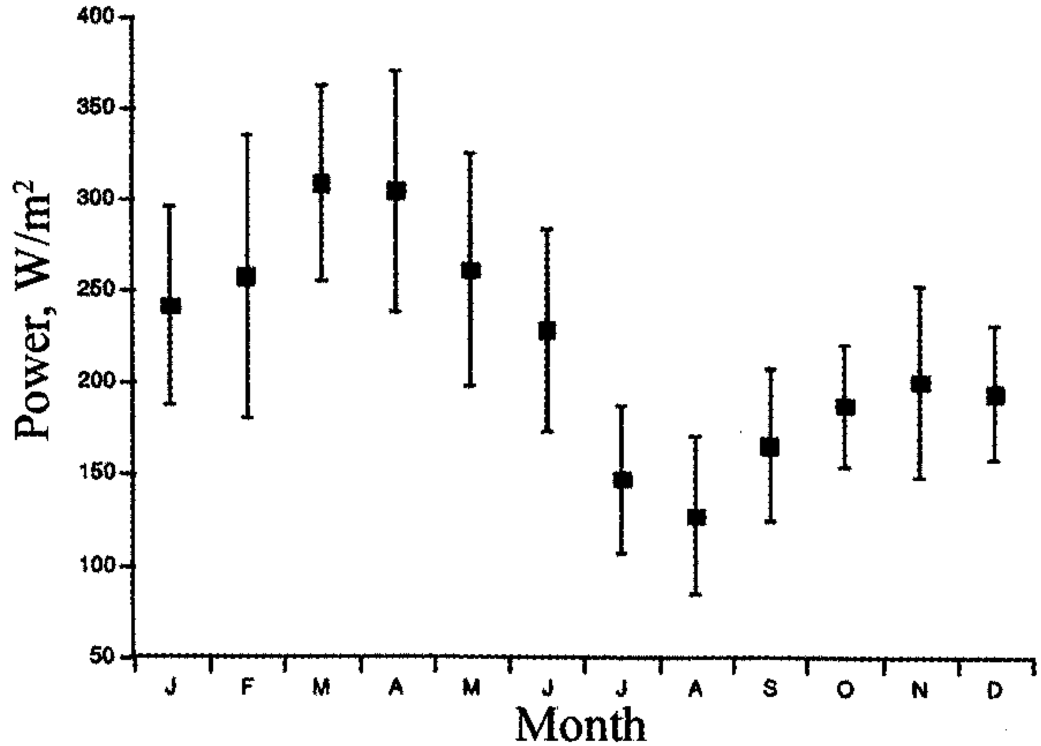


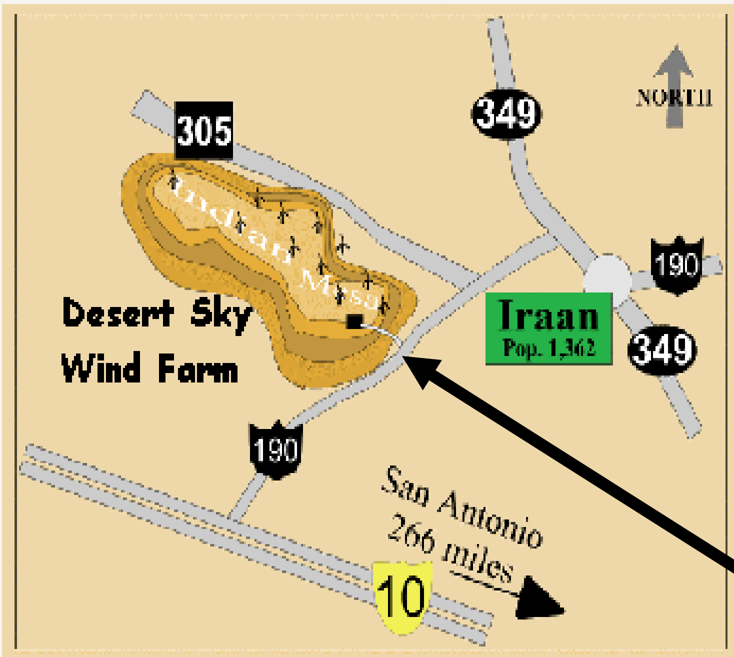
Figure 2.7 Seasonal variation of available wind power per unit area for Amarillo, Texas (Rohatgi and Nelson, 1994). Reproduced by permission of Alternative Energy Institute

Desert Sky Wind Farm

www.desertskywind.com

AEP WIND ENERGY

Desert Sky Wind Farm - Map

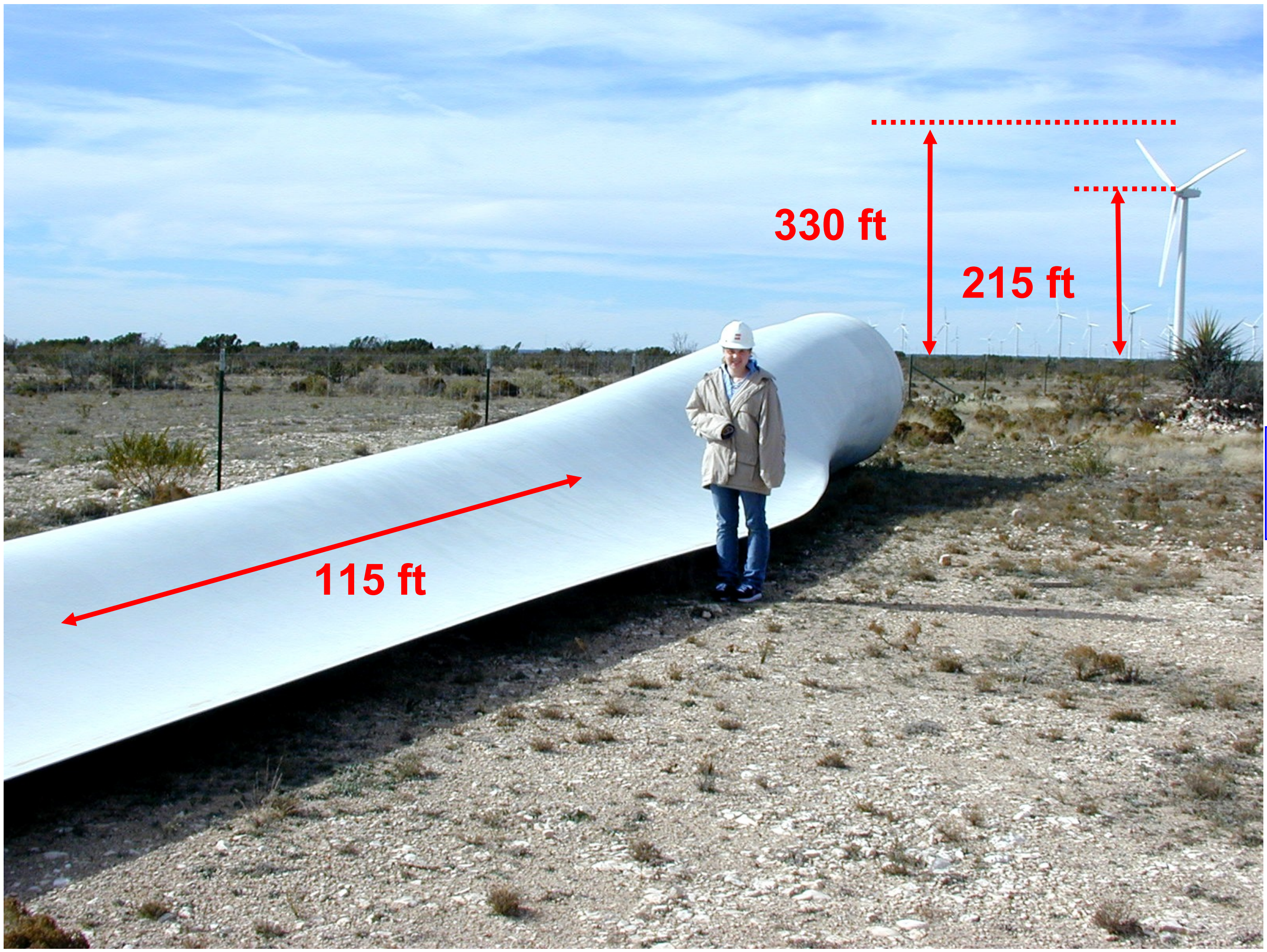


- Dallas - 400 Miles
- San Antonio - 266 Miles
- Odessa - 90 Miles

- Ft. Stockton - 50 miles
- McCamey - 20 Miles
- Iraan - 12 Miles

AEP WIND ENERGY

Desert Sky Wind Farm
(approx 300 miles due west of Austin)



At least 100 wind turbines in a wind farm

Approx. 10 wind turbines (15 MW) per square mile. Thus, a farm needs at least 10 square miles.

Metric units – about 6 MW per square km.

Operate at 10 – 20 RPM, with wind speed range 8 – 56 MPH

Desert Sky Wind Farm

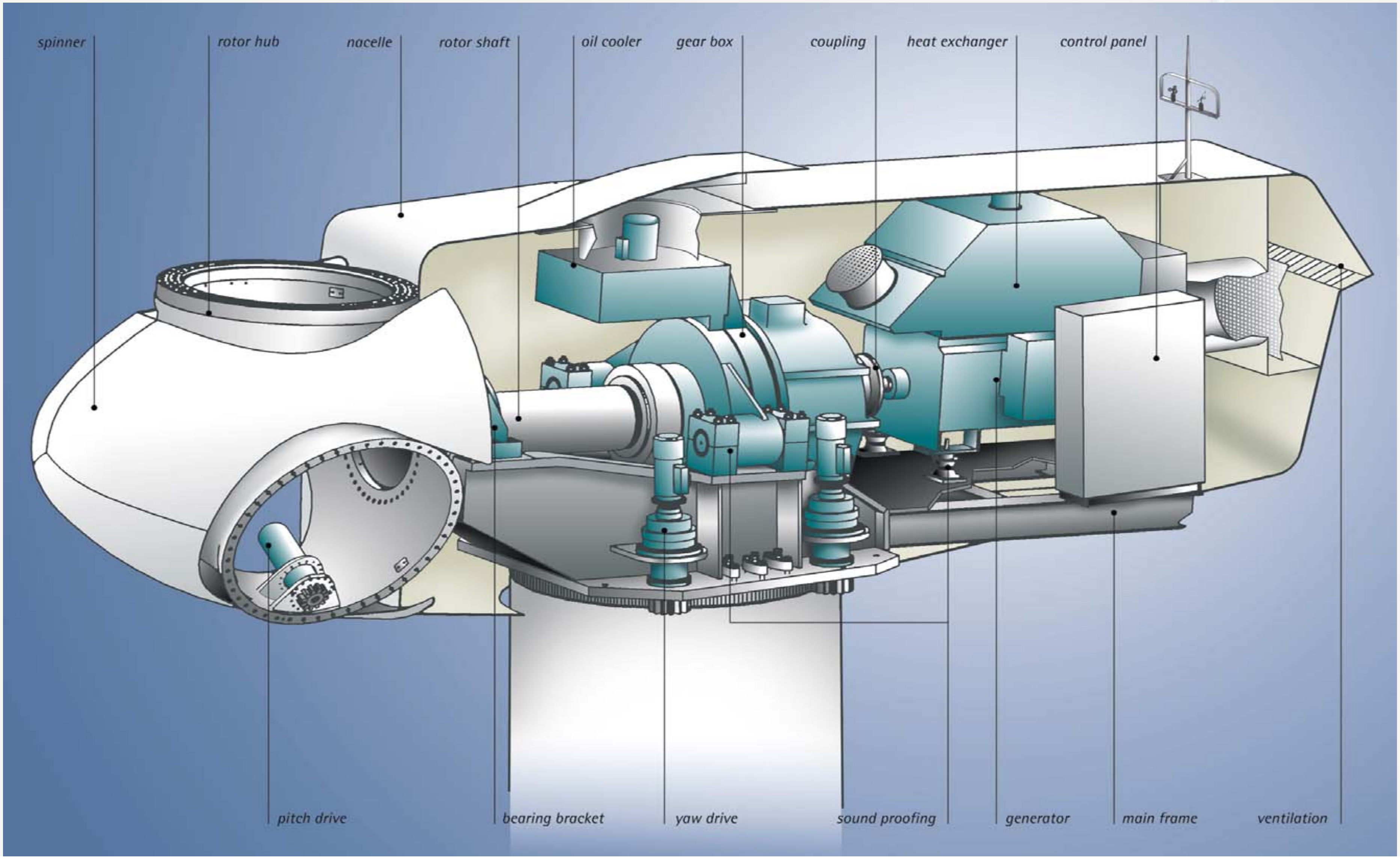
- Commercial operation - Jan '02
- 160 MW Project
  - One hundred seven 1.5 MW **turbines**
  - 211 ft (65 meter) hub height
  - 229 ft (70.5 meter) rotor diameter
  - Total height of 329 ft (101 meters) to top of blade tip to base
- Project occupies about 16 square miles
- One substation with two transmission interconnects

GE 1.5S Wind Turbine Operation

- Operates in 8-56 mph wind speeds
- Each turbine is a self-contained independent power plant, no operator intervention required
- Onboard weather station, yaw control facing wind
- Variable speed, operates from 10-20 RPM rotor/blade assembly, generator speeds 850 to 1440 RPM

AEP WIND ENERGY

Nacelle Layout



Technical Talking Points

*6 pole machine, Synchronous speed 1200 rpm.

*Converter operation (Variable speed machines), Sub-synchronous/super-synchronous operation

*Gearbox Operation (1:72 ratio)

*Low Voltage ride through

*Collection system/substation design

*Transmission system issues (congestion)

*Power Factor/ VAR control/Transmission system voltage control

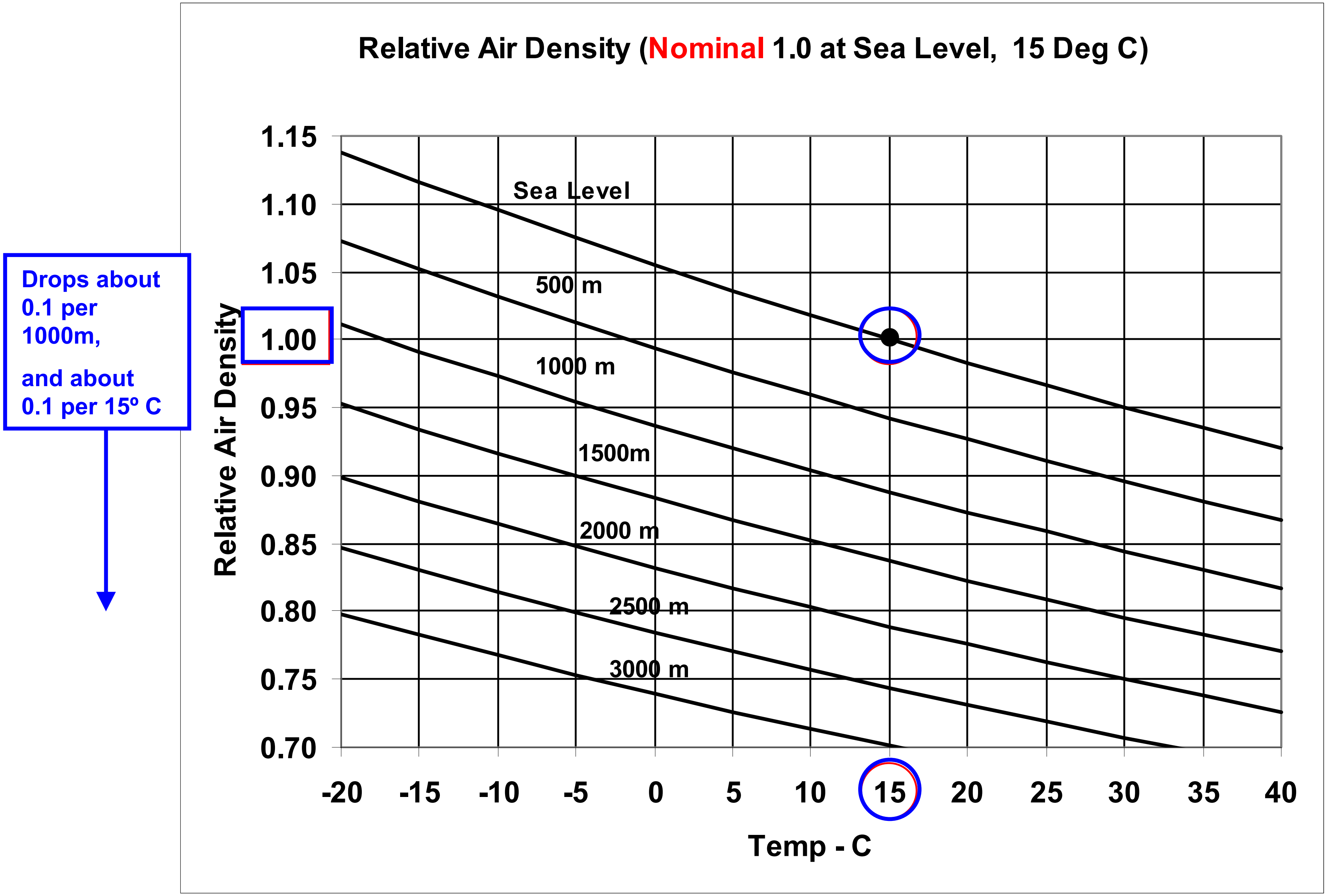
*Non-dispatchable nature of wind power/renewable energy systems in general

*Climb assists

O&M - Non-Routine Corrective Maintenance

- **Blade repairs, lightning damage & leading edge erosion.**
  - Blade inspections and repairs are completed annually.
  - About 25 lightning related repairs per year.
    25 lightning-related repairs per year per 100 turbines
  - Since commissioning, three blades have required replacement due to lightning damage.
- **Gearbox failures and subsequent replacement.**
  - Gearbox life cycle appears to be 5-8 years.

Note: The repairs mentioned above require two cranes, a large 300 ton crane and a smaller 100 ton crane. Crane availability and expense are serious issues facing wind farm owners. Demand for crane service is currently outpacing availability.


Relative Air Density (Nominal 1.0 at Sea Level, 15 Deg C)
Drops about 0.1 per 1000m,
and about 0.1 per 15º C
Relative Air Density
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
Sea Level
500 m
1000 m
1500m
2000 m
2500 m
3000 m
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
Temp - C

Betz Limit – Max theoretical turbine energy capture = 59.3% of swept area when downwind is slowed to 1/3rd of the upwind speed.

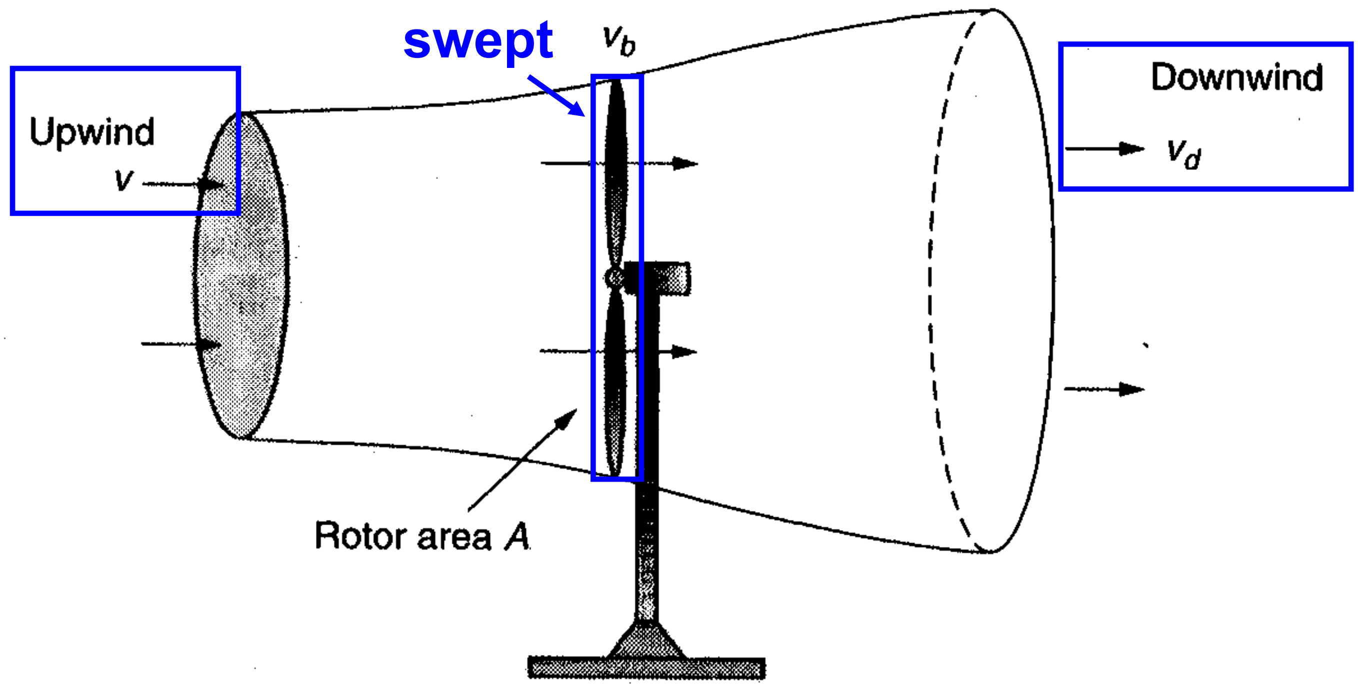


Figure 6.9 Approaching wind slows and expands as a portion of its kinetic energy is extracted by the wind turbine, forming the stream tube shown.

Betz Limit – Max theoretical turbine energy capture = 59.3% of swept area when downwind is slowed to 1/3rd of the upwind speed.

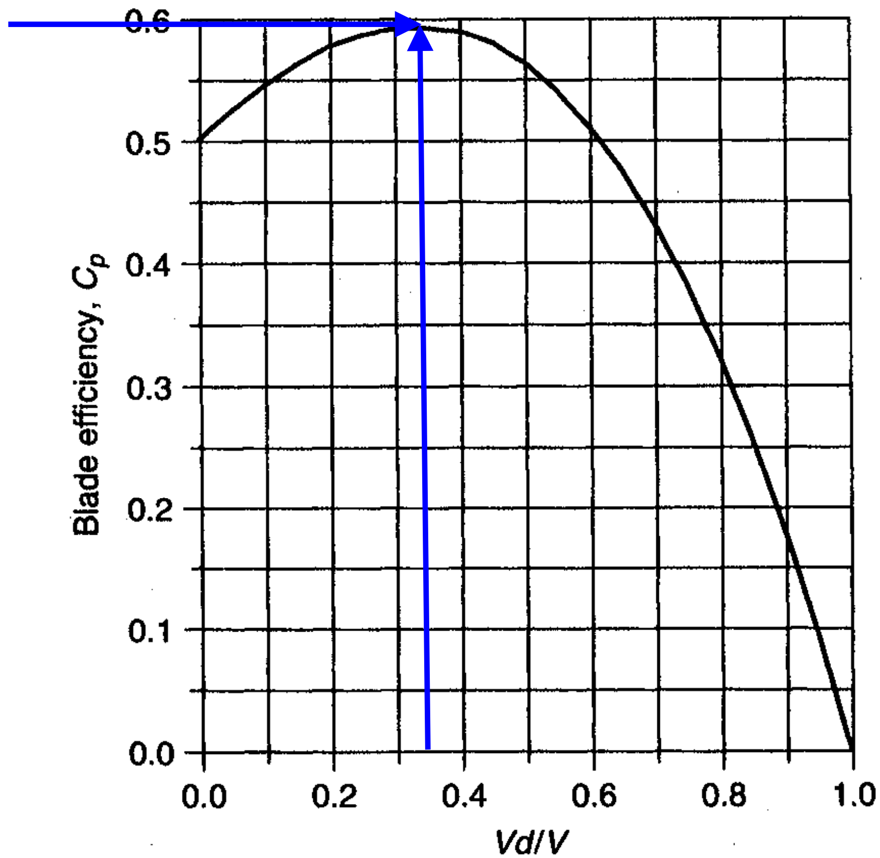


Figure 6.10 The blade efficiency reaches a maximum when the wind is slowed to one-third of its upstream value.

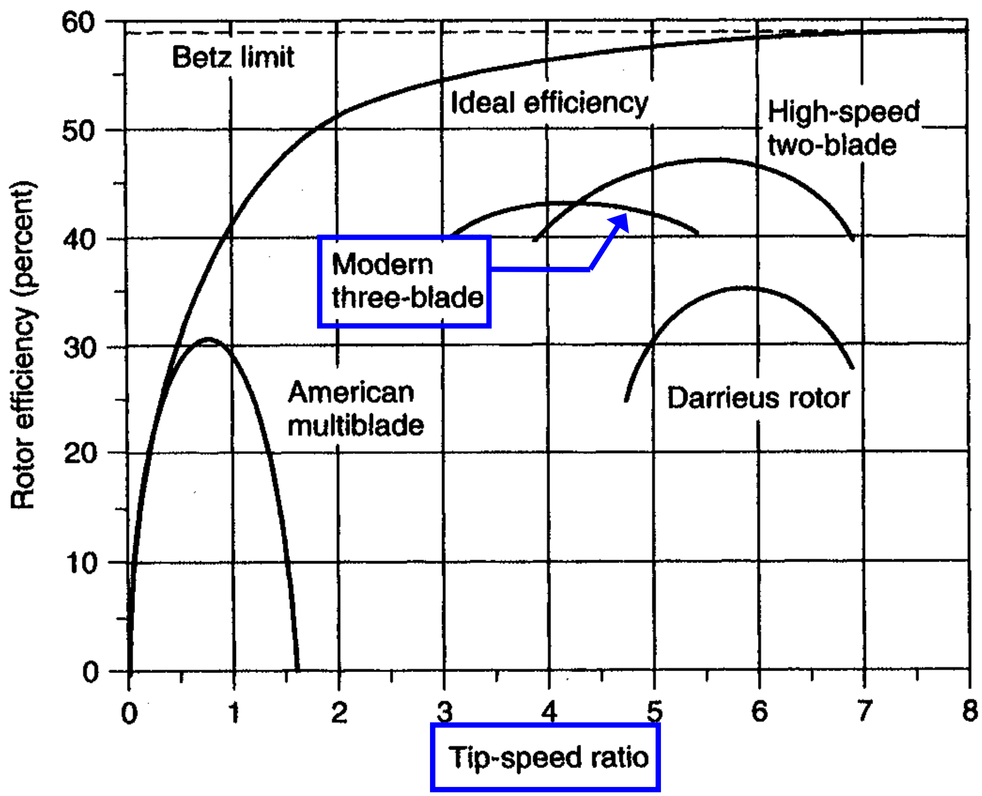


Figure 6.11 Rotors with fewer blades reach their optimum efficiency at higher rotational speeds.

$$TSR = \frac{Tip\ Speed}{v_{wind}} = \frac{\omega_{rotor}\,(rad/\sec) \bullet R_{rotor}\,(m)}{v_{wind}\,(m/\sec)}$$

Response from Roy Blackshear, Manager of Desert Sky Wind Farm

- We reach rated power at about 12.5 m/s or 28 mph at an air density of 1.09, which was originally calculated as the year round average for this site.

- When wind speeds exceed rated, i.e., >12.5 m/s, the blades pitch-regulate to maintain rated output and rotor speed at slightly over 20 rpm.

- **Turbines** pitch blades out of the wind if 10 minute average wind speeds exceed 25 m/s or 56 mph, or wind speeds of > 28 m/s for 30 seconds, or storm gusts of 30 m/s or 67 mph.

Roy Blackshear, cont.

- Lower ambient temperatures in the winter increase the air density substantially, resulting in improved performance of about 5% on the coldest days.
- In general, the change in performance is subtle and only apparent where ambient temperatures are very low, below freezing.

From GE Wind Energy Basics

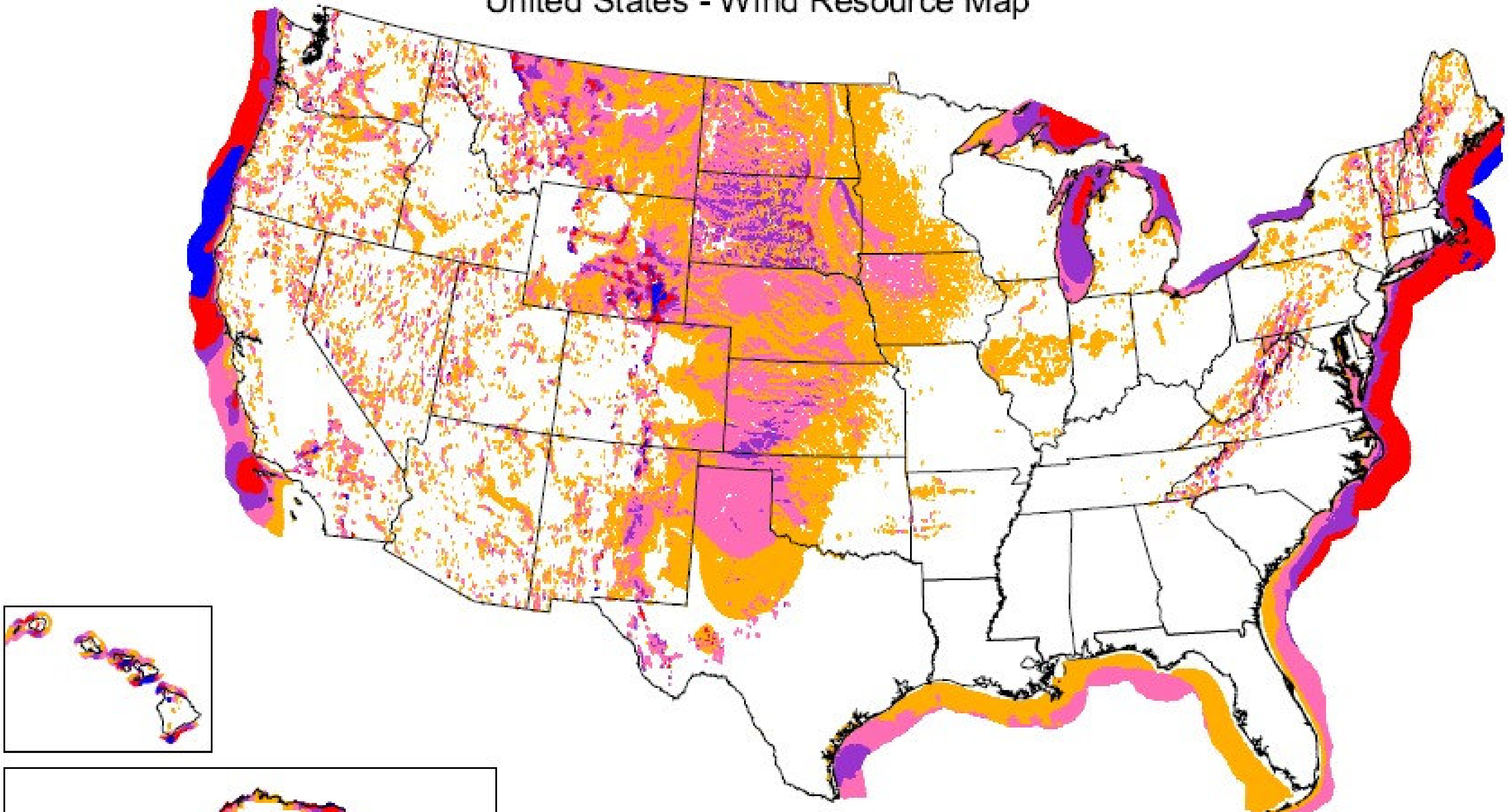
Q. How much does a wind farm cost?

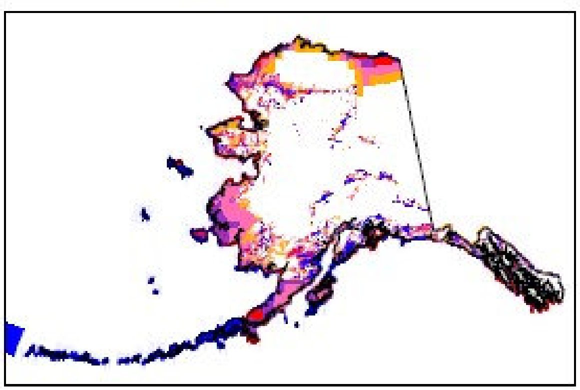
A. The total cost will vary significantly based on site-specific conditions, permitting and construction requirements, and transportation constraints. In general wind power development can cost around $2 million per megawatt (MW) of generating capacity installed, including supporting infrastructure commonly referred to as Balance of Plant (BoP).

Q. How big are wind turbines?

A. The "tip height" of a GE 1.5 MW turbine is approximately 120 meters, which represents the total height of tower plus a blade in its highest vertical position.

United States - Wind Resource Map





Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m[2]	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

Moderate: 6.4 - 7 m/s

Good: 7- 7.5 m/s

Excellent: >7.5 m/s

U.S. Department of Energy
National Renewable Energy Laboratory

Wind Energy’s Potential

- Wind power accounted for about 42% of all new power generating capacity added in the US in 2008, representing one of the largest components of new capacity addition.

- Wind energy could supply about 20% of America's electricity, according to Battelle Pacific Northwest Laboratory, a federal research lab. Wind energy resources useful for generating electricity can be found in nearly every state.

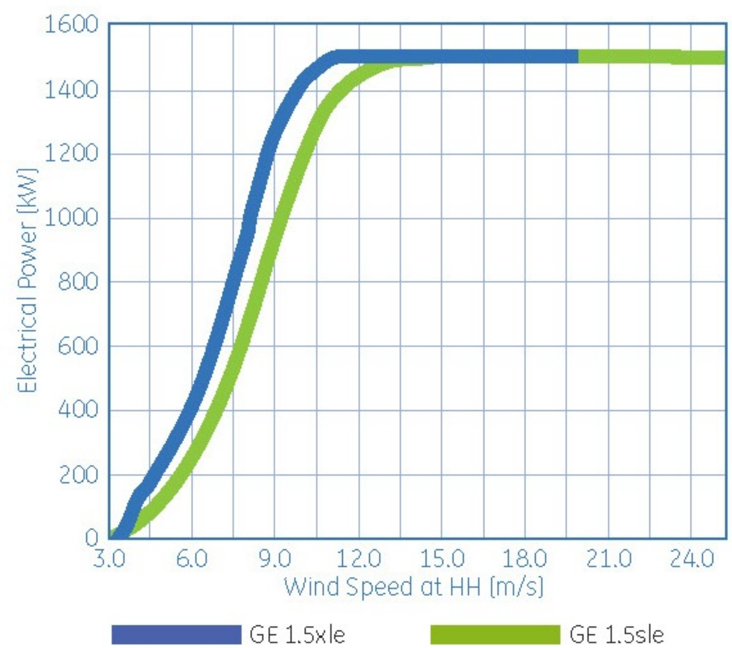
- Wind is projected to deliver 33% of all new electricity generation capacity and provide electricity for 86 million Europeans by 2010.

GE 1.5MW Turbines

Technical data

		1.5sle	1.5xle
Operating Data			
Rated Capacity:		1,500 kW	1,500 kW
Temperature Range: (with Cold Weather Extreme Package)	Operation:	-30°C – +40°C	-30°C – +40°C
	Survival:	-40°C – +50°C	-40°C – +50°C
Cut-in Wind Speed:		3.5 m/s	3.5 m/s
Cut-out Wind Speed (10 min avg):		25 m/s	20 m/s
Rated Wind Speed:		14 m/s	11.5 m/s
Wind Class — IEC:		IIa (V_{e50} = 55 m/s V_{ave} = 8.5 m/s)	IIIb (V_{e50} = 52.5 m/s V_{ave} = 8.0 m/s)
Electrical Interface			
Frequency		50/60 Hz	50/60 Hz
Voltage		690V	690V
Rotor			
Rotor Diameter:		77 m	82.5 m
Swept Area:		4657 m^2	5346 m^2
Tower			
Hub Heights:		65/80 m	80 m
Power Control		Active Blade Pitch Control	Active Blade Pitch Control

Power curve



1.5sle — *Classic workhorse, an efficient and reliable machine with proven technology*

1.5xle — *Built on the success of the 1.5sle platform, captures more wind energy with 15% greater swept area*

MITSUBISHI WIND TURBINE GENERATOR

MWT102/2.4

Technical Data

Operation Data

Cut-in	3.0 m/s
Rated	11.5 m/s
Cut-out	25.0 m/s
Wind Class	IEC Class IIA

Rotor

Diameter	102 m
Swept Area	8,171 m^2
Rotational Speed (rated)	15.0 rpm
Rotational Speed (interval)	9.0 ~ 16.9 rpm (variable)
Blade Length	49.7 m
Aerodynamic Brake	Individual Pitch Brake

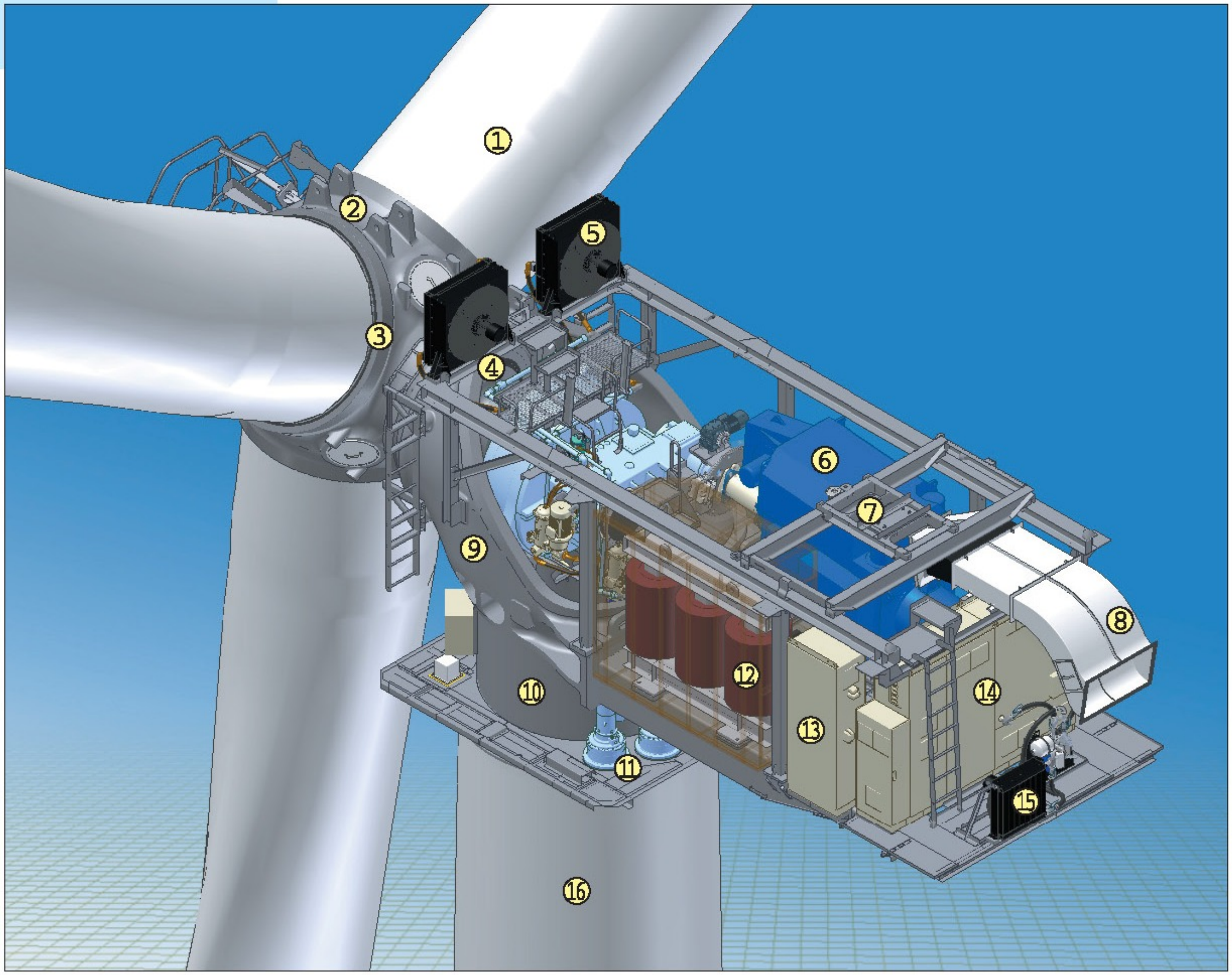
Generator

Type	Doubly Fed Asynchronous Generator + IGBT Converter
Rated Power	2,400 kW
Voltage	690 V
Frequency	50 Hz/60 Hz
Power Factor Range	0.9 (inductive) ~ 0.95 (capacitive)

Tower

Hub Height	80 m

• High performance in moderate wind speed area (IEC Class IIA) • Individual pitch control

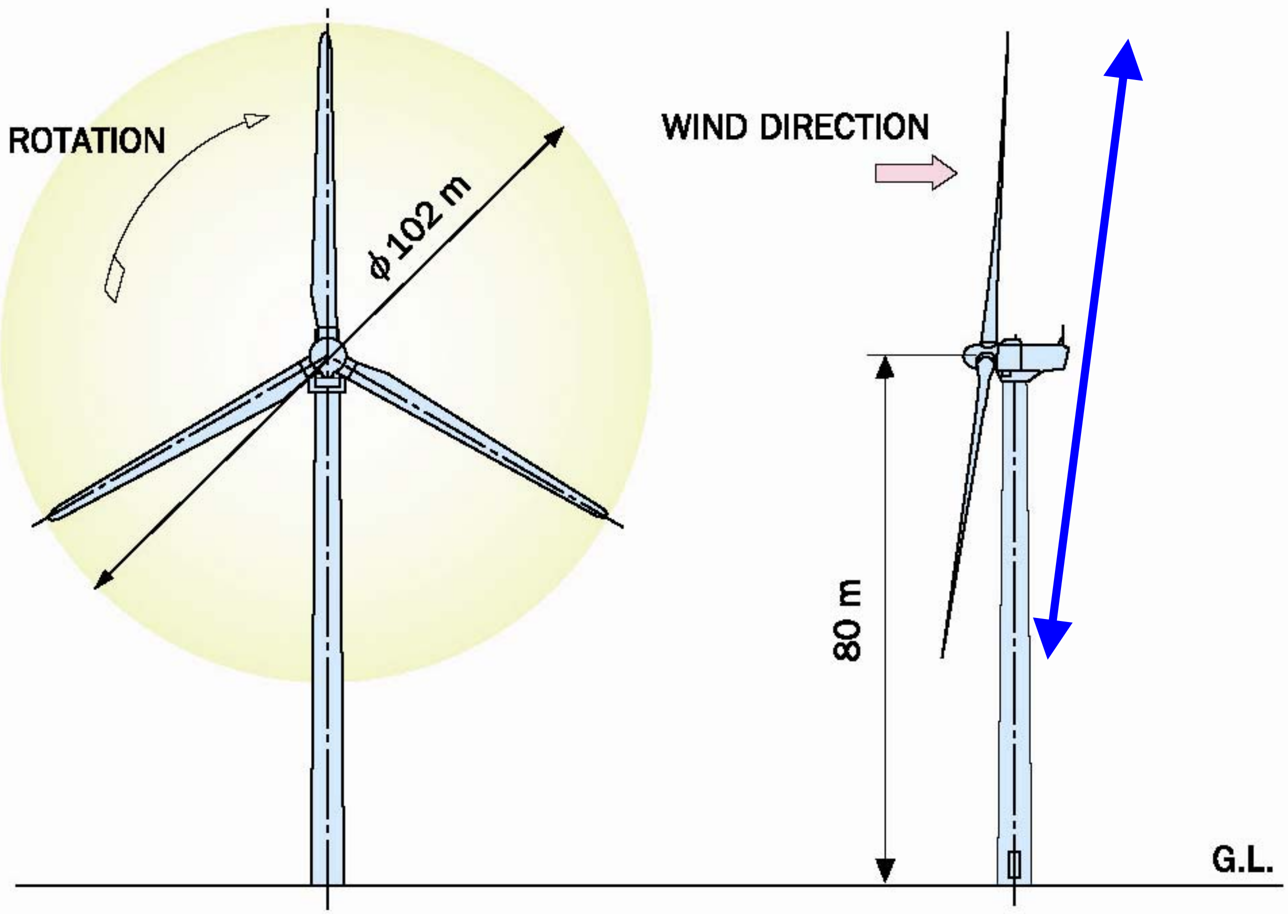


Schematic Diagram

① Blade	⑤ Oil Cooler	⑨ Nacelle Bed Plate	⑬ Control Panel
② Hub	⑥ Generator	⑩ Yaw Bearing	⑭ Inverter
③ Blade Bearing	⑦ Service Winch	⑪ Yaw Gear	⑮ Cooler for Inverter
④ Main Bearing	⑧ Exhaust Duct for Generator	⑫ Transformer	⑯ Tower

Tower

Hub Height 80 m



EE411, Fall 2011, Lab. 4. Phase-Locked Loop

In Lab 1, you manually followed the 120Vac grid voltage by adjusting an external waveform generator. In Lab 4, you will perform the same feat using your built-in pulse generator, and also automate the process using a phase-locked loop with proportional-integral (PI) controller. A phase-locked loop "locks" the phase and frequency of the built-in pulse generator with the 120Vac voltage.

In Lab 1, you used the following cosine product trig expression:

$$\cos(\omega_1 t + A) \bullet \cos(\omega_2 t + B) = \frac{1}{2}\left[\cos\{(\omega_1 - \omega_2)t + A - B\} + \cos\{(\omega_1 + \omega_2)t + A + B\}\right]$$

which (see page 13) gives positive error in the first "beat frequency" term when the two signals are in phase, zero error when they are 90º out of phase, and negative error when they are 180º out of phase. In Lab 4, you will use the following sine, cosine product to achieve zero error in the beat frequency term when the two signals are in phase (i.e., "phase locked"). The sine term is obtained by integrating the grid voltage.

$$\sin(\omega_1 t + A) \bullet \cos(\omega_2 t + B) = \frac{1}{2}\left[\sin\{(\omega_1 - \omega_2)t + A - B\} + \sin\{(\omega_1 + \omega_2)t + A + B\}\right]$$

A PI controller converts a first-order response system (such as an RC or RL circuit) to a second-order response system so that error can be quickly minimized. Our "system," which is essentially the relationship between the RF3 knob and the pulse generator frequency, is not exactly first-order, but nevertheless it can be approximated as such. You will replace RF3 with a MOSFET, which in our case will be a voltage-controlled resistor. A feedback voltage based upon error and integral of error adjusts the pulse generator frequency to achieve "locking."

Theory follows on the next few slides. This material is taken from EE462L Power Electronics and illustrates how a PI controller regulates the output voltage of a DC-DC converter.

EE411, Fall 2011, Lab. 4. Phase-Locked Loop, cont.

A proportional-integral controller (i.e., PI) with feedback can take the place of manual adjustment of the switching duty cycle to a DC-DC converter and act much more quickly than is possible "by hand." Consider the Transformer, DBR, MOSFET Firing Circuit, DC-DC Converter, and Load as "a process" shown below. In the open loop mode that you used last time, you manually adjusted duty cycle voltage Dcont.

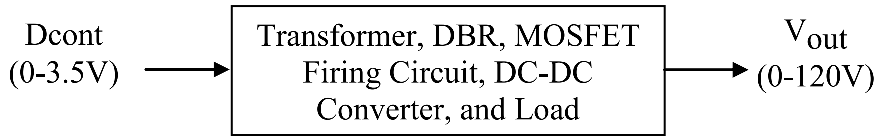


Figure 1. Open Loop Process

To automate the process, the "feedback loop" is closed and an error signal (+ or –) is obtained. The PI controller acts upon the error with parallel proportional and integral responses in an attempt to drive the error to zero.

Let αV_{out} be a scaled down replica of V_{out}. When αV_{out} equals V_{set}, then the error is zero. A resistor divider attached to V_{out} produces αV_{out}, which is suitably low for op-amps voltage levels.

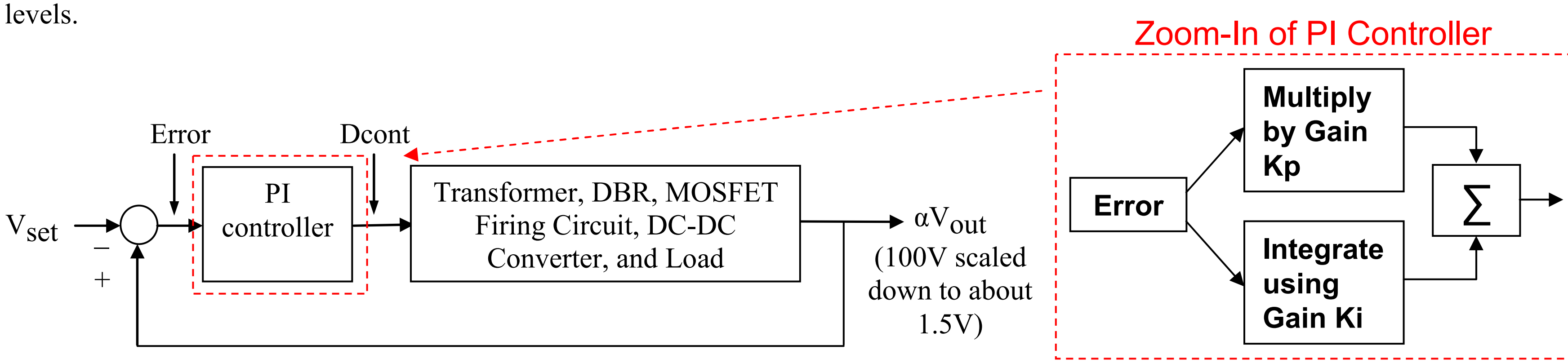
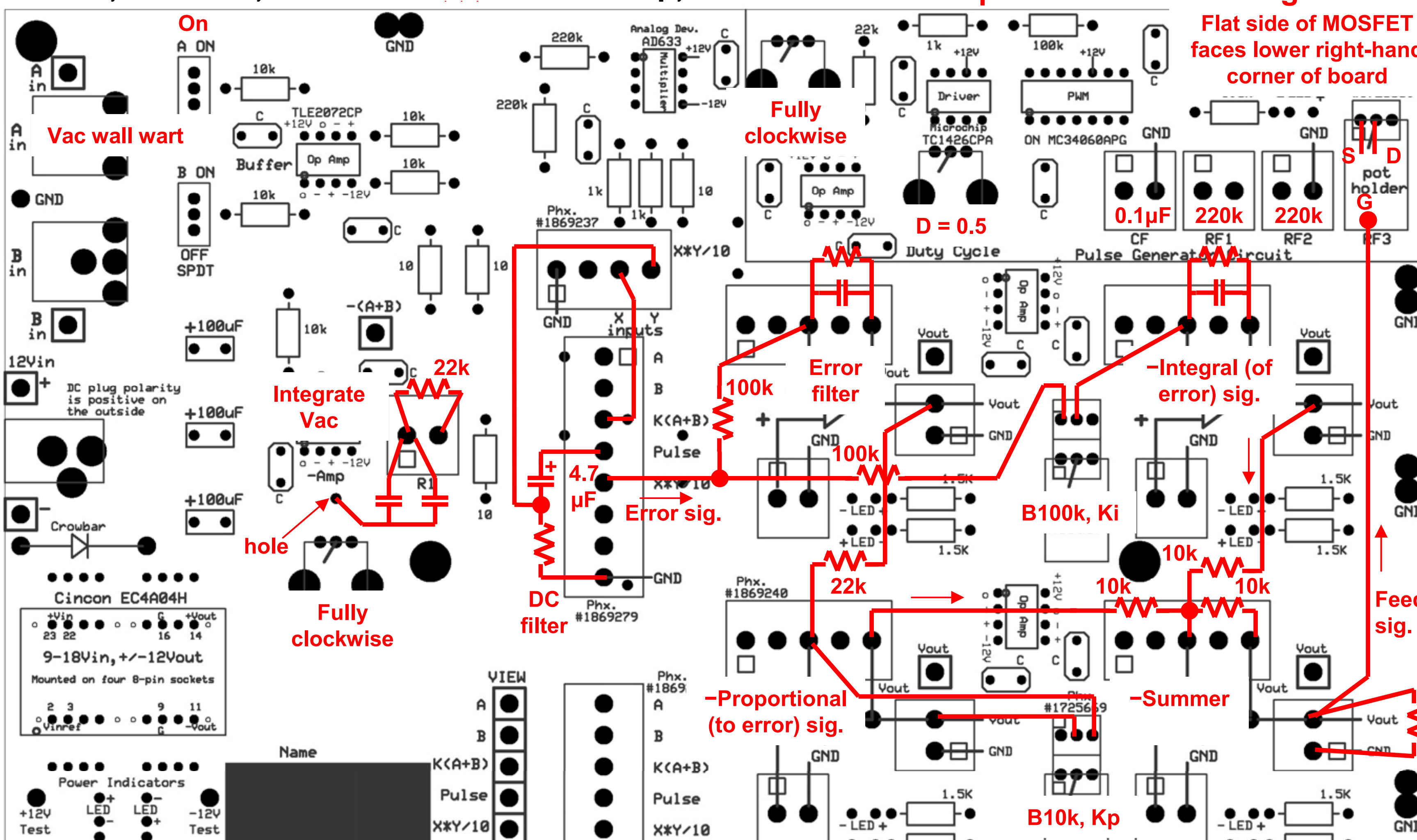


Figure 2. Closed Loop Process with PI Controller

EE411, Fall 2011, Lab. 4. Phase-Locked Loop, cont.

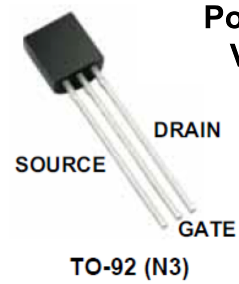
Wire up with #24 solid orange



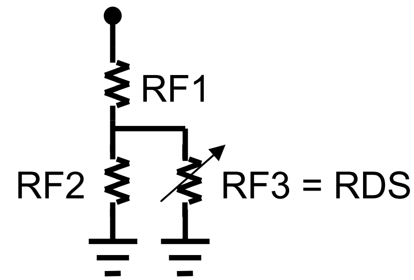
1 Unmarked red resistors are 220k. Unmarked red capacitors are 0.1µF. The 4.7µF capacitor is polarized and the + terminal is marked. Bottom leads of twin caps in "Integrate Vac" are pushed through the holes below the amp – tack soldering them to the board is advisable. The MOSFET is a voltage-controlled resistor − raise voltage Vgs, and MOSFET resistance Rds decreases. G,D,S are MOSFET gate, drain, source. The integral of Vac is on pin K(A+B).

EE411, Fall 2011, Lab. 4. Phase-Locked Loop, cont.

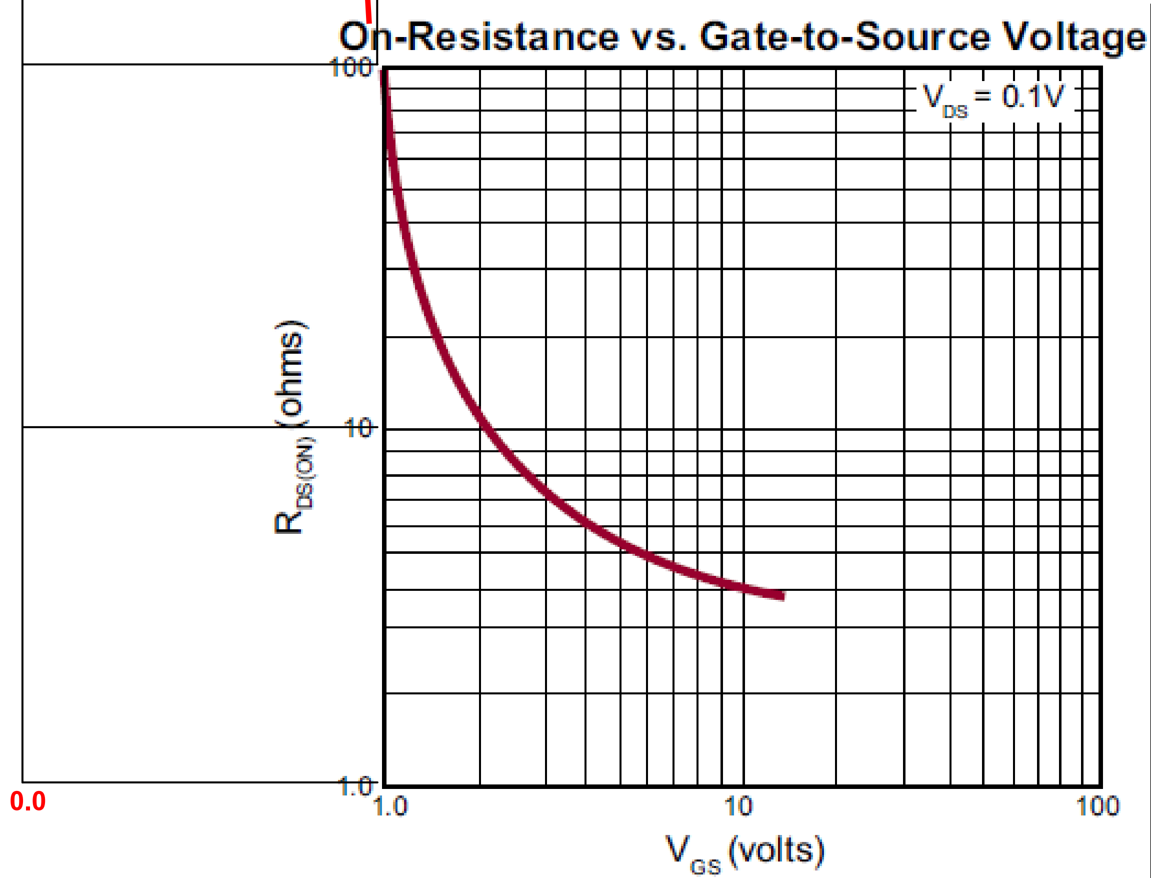
Pin Configuration



Supertex MOSFET Power 60V, 5Ω, VN10KN3-G



RF for Pulse Generator equals RF1 + RF2 || RF3

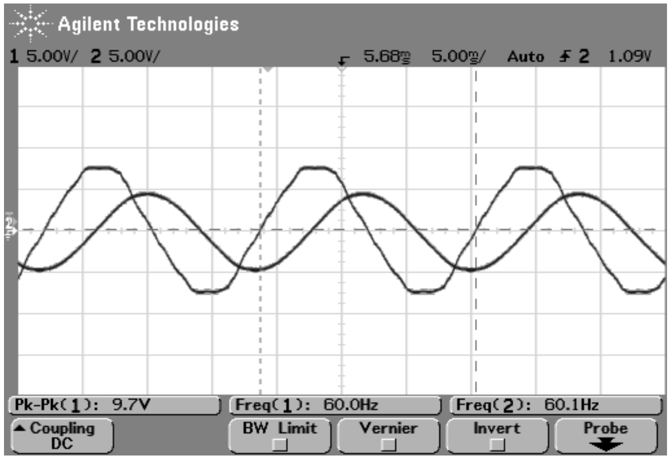


Free-Running Tests. RF1 = RF2 = 220kΩ, CF = 0.1μF.

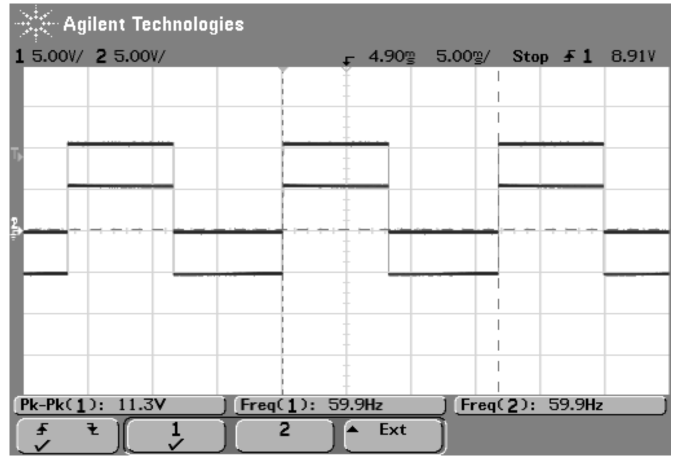
1. When **MOSFET is removed**, RF = 440kΩ, and computed F = 27Hz **(actual measurement is 33Hz),**
2. When RF3 is shorted, which is essentially the same situation as **MOSFET "on,"** RF = 220kΩ, and computed F = 55Hz **(actual measurement is 66Hz),**
3. When **MOSFET is inserted but "off," with its open gate terminal connected to ground through a 1kΩ resistor, the actual measurement is 55Hz.** Backcalculating, RF = 264kΩ, thus **MOSFET "off" resistance is 55kΩ.**
4. You may need to vary CF or RF1 to achieve a range of frequency similar to the 55-to-66Hz range in Steps 2-3 above. The range should be approx. centered around 60Hz.

EE411, Fall 2011, Lab. 4. Phase-Locked Loop, cont.

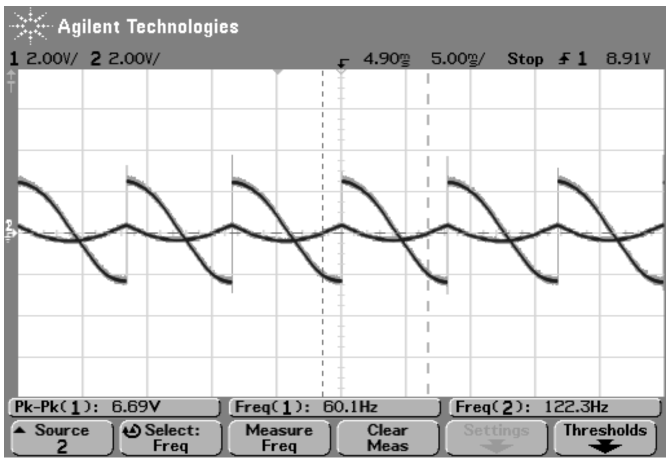
Checkpoint Screen Snapshots, Taken When "Locked"



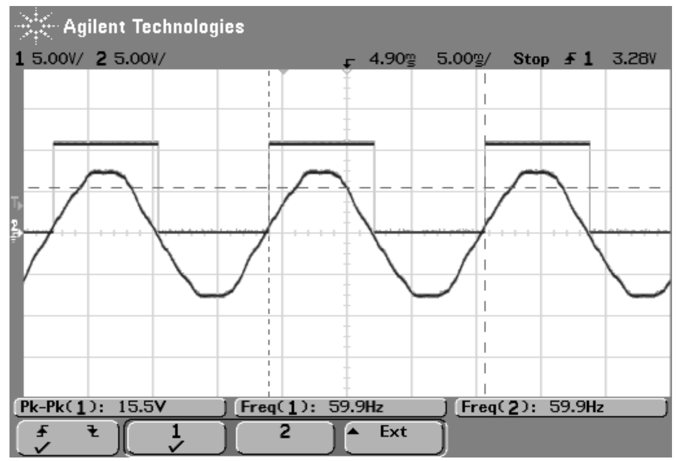
1. Vac (pin A), and integral of Vac (pin K(A+B))



2. Pulse generator (pin PULSE), and pulse generator with DC removed (multiplier input Y)

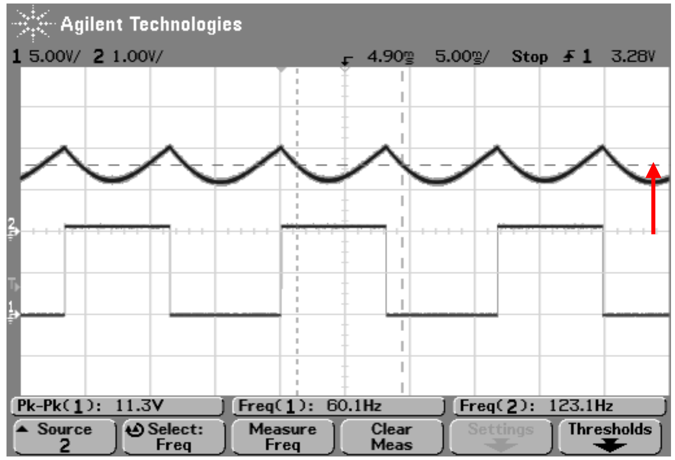


3. Error signal (pin X*Y/10) and filtered error signal (error filter op amp Vout)



4. Vac (pin A), and pulse generator (pin PULSE). Pulse is steady when locked.

EE411, Fall 2011, Lab. 4. Phase-Locked Loop, cont.



Vgs about 1.5V avg

5. PULSE and MOSFET gate voltage Vgs