TECHNICAL MEMO 2015-004

Infrasound Measurements of Falmouth Wind Turbines Wind #1 and Wind #2

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0.0 EXECUTIVE SUMMARY

Noise Control Engineering, LLC (NCE) was retained by Senie & Associates P.C. to evaluate the acoustic impact at the home of Neil and Betsy Andersen at 211 Blacksmith Shop Road, East Falmouth, Massachusetts. The goal of the evaluation was to determine if the three nearby wind turbines were detectable within the interior of the home. These wind turbines are all Vestas, model V82 at 1.65 megawatts. Two wind turbines are owned by the Town of Falmouth; known as "Wind #1" and "Wind #2". The third turbine is privately owned by Notus Clean Energy and referred to as the "Notus" turbine. Wind #1 is the closest to the Andersen home at a nominal distance of 1,385 feet. The other two wind turbines are more than double that distance.

Soon after the first wind turbine was operational, complaints were filed by the Andersens and other neighbors. In the following years, evaluations of audible sound were performed by various organizations including NCE, consultants for the Town, consultants for Notus, and even the Massachusetts Department of Environmental Protection (MADEP). Various results were reported with some evaluations showing compliance and some showing non-compliance.

The study reported herein differed in a number of ways from previous evaluations performed by NCE and others. The major difference is that the primary measurements reported here is infrasound. Briefly, *infrasound* is sound pressure levels with frequency below 20 hertz which is generally considered an inaudible frequency range. Another difference is that measurements were taken both inside and outside the home. All previous tests were performed at exterior locations due to the fact that State regulations and local ordinance were only applicable at outdoor locations.

The methods used herein allowed for the collection of infrasonic sound pressure levels within the inside of the Andersen residence. Inspection of this data shows that there is a readily identifiable acoustic signature that is attributable to the Wind #1 Turbine, and to slightly lessor extent the Wind #2 turbine both inside and outside the Andersen home. These results are similar to results from other international researchers with references given in the report.

Based on our experience, NCE can unequivocally state that the infrasonic signature captured inside the Andersen residence with the wind turbines operational is 100% attributable to one or both of the Town's Wind Turbines. To put the conclusions more commonly, this study finds that the wind turbine(s) produce acoustic emissions which are "acoustically trespassing" into the Andersen home.

1.0 INTRODUCTION

Noise Control Engineering, LLC (NCE) was retained by Senie & Associates P.C. of Westborough, Massachusetts to evaluate the acoustic impact at the home of Neil and Betsy Andersen at 211 Blacksmith Shop Road, Falmouth, Massachusetts. The goal of the evaluation was to determine if the sound from the nearby wind turbines is detectable within the interior of the home. This evaluation was conducted by measuring infrasound.

2.0 BACKGROUND

In 2010 the Town of Falmouth erected the first of two Vestas V82, 1.65 megawatt wind turbines, known as "Wind #1" and in 2012 the second turbine known as "Wind #2" was installed. Also in 2010, Notus Clean Energy erected the same Vestas V82 wind turbine known as the "Notus" wind turbine. Appendix A provides a copy of the equipment data sheet for information only. Figure 1 shows the locations of the three wind turbines in relation to the Andersen Home at 211 Blacksmith Shop Road. As shown in Figure 1, Wind #1 is the closest to the residence with a distance of 1,385 feet. Wind #2 is 2,600 feet and Notus is 3,900 feet from the residence[1].

Soon after the first wind turbine was operational, complaints were filed by the Andersens and other neighbors. In the following three years, evaluations of audible sound (20 to 20,000 hertz) were performed by many different organizations. NCE conducted some of the first sound measurements and reported these results to the Town of Falmouth during a meeting with the Board of Selectman (reference 1). NCE identified a characteristic time domain pattern known as "Amplitude Modulation" which demonstrated excess to the Town of Falmouth 40 dB(A) wind turbine sound ordinance (reference 2).

Following this work a series of evaluations were performed by another consultant, Harris Miller Miller & Hanson (HMMH) under contract to the Town's engineering firm that supervised the installation of the wind turbines. The purpose of this evaluation was to compare acoustic performance to the Massachusetts Department of Environmental Protection (MADEP) noise regulation[2] (reference 3). The wind turbines were found to be somewhat in compliance in both assessment reports which evaluated the data using two different approaches, (references 4, 5). However, the results showed that 4 dB to 15 dB increases in broadband sound over the background sound occurred depending on the measurement location (reference 4, 5).

Another consulting firm, Epsilon Associates, Inc. evaluated the Notus wind turbine and reported results in reference 6. This study evaluated the wind turbine sound with respect to the Falmouth Special Permit conditions, reference 7. The special permit conditions required no more than a 6 dB increase in A-weighted sound pressure level, no pure tones and no more than 6 dB increase in infrasound. The Town of Falmouth Zoning Board of Appeals applied a 6 dB allowance over background noise for Notus and in connection with one other privately owned turbine. In 2013 the Falmouth Town Meeting adopted the 6 dB limitation as a Town-wide zoning provision applicable to all wind turbines. The Epsilon report found that the wind turbine was compliant for

[1] All distances are nominal and determined using Google Earth.
[2] Compliance with the State regulations requires two conditions: (1) the source of sound cannot produce an A-weighted sound pressure (SPL) level that is greater than 10 decibels above the background A-weighted SPL and (2) the source of sound cannot produce a "pure tone"

all three conditions. However, the infrasound condition was found to have an increase of as much as 5.7 dB.

Lastly, in 2012, the MADEP conducted their own set of measurements using only MADEP staff from the Lakeville office. Attended measurements were performed on multiple days during both the nighttime (reference 8) and daytime (reference 9). The nighttime report found that Wind #1 exceeded the 10 dB regulation while the daytime report found no excess to the 10 dB regulation.

In summation, the purpose of this section is to indicate the variety of acoustical evaluations that were performed of the Falmouth turbines (Wind #1, Wind #2 and Notus). Three different acoustical consulting groups conducted surveys for three different clients (Town of Falmouth, Notus Clean Energy, and residence groups) and compared results to three different sets of requirements (Falmouth Wind Turbine ordinance, Notus, special permit, and MADEP regulations). Within all these evaluations, various degrees of compliance and non-compliance were declared.

3.0 TEST OVERVIEW

This evaluation differs in a number of ways from previous tests performed by NCE and others as noted in Section 2. The major difference is that the primary measurements performed herein are “infrasound”. Briefly, infrasound is sound pressure levels with frequency below 20 hertz which is generally considered an inaudible frequency range. Another difference to previous studies is that measurements were taken both inside and outside the home. All previous tests described in Section 2 were performed at exterior locations due to the fact that State regulations and the local ordinance were only applicable at outdoor locations.

As noted in Section 2, the Falmouth Wind Turbines were found to be out of compliance with MADEP regulations. To be out of compliance with MADEP noise regulations requires that the source of noise (the Wind Turbines) have an A-weighted sound pressure (SPL) level that is 10 decibels above the background A-weighted SPL. This condition was usually found to occur in the late evening and overnight, not because the wind turbine sound increased, but mostly because the background sound decreased during the night. Because of this situation, the court ordered (reference 10) that both Wind #1 and Wind #2 be shut down during the hours of 7pm to 7am. As such, the infrasound measurements were performed from the hours of 5pm to 8pm to allow for easy comparison of the measured infrasound with and without the Wind #1 and Wind #2 operating.

4.0 INSTRUMENTATION

Infrasonic SPL was measured using a Bruel & Kjaer infrasonic microphone, model 4964. The frequency response is useable within ±1 dB accuracy from 0.04 to 8,000 Hz[3]. The system was field calibrated by a Larson Davis model CAL200 calibrator at 94 dB (relative to 20 micro-Pa) at 1,000 Hz. The microphone was covered with a standard wind screen and mounted on a tripod at a nominal height of 5 feet above the ground for all measurements.

[3] ±2 dB from 0.03 to 20,000 Hz and ±3dB is from 0.02 to 20,000 Hz

Data acquisition was performed using a National Instruments, model 9234 4-channel data acquisition module. The software used is based on the National Instruments Sound & Vibration Toolkit. The system is configured to collect narrowband sound spectrum measurements using the Fast Fourier Transform (FFT) signal processing algorithm. The FFT settings were slightly differently for each of the four visits as the test methods were refined. The typical settings were 20,480 lines, 0.05 hertz resolution, 10 averages (200 seconds of sampling, 3.3 minutes), and a Hanning window.

All acoustic instrumentation was laboratory calibrated to NIST standards by an accredited laboratory within the past 12 months. Calibration certificates will be provided upon request.

5.0 RESULTS

Infrasonic measurements were performed during 4 visits to the Andersen residence between July 2014 and February 2015. Table 1 provides a summary for each visit including date, time of day, and wind conditions.

Table 1: Site Visit Date, Time, and Wind Conditions

Measurement Date	Approximate Start Time	Wind	
		Direction	Speed
July 5, 2014	1:30 pm	Northwest	17 mph
November 21, 2014	6:30 pm	Southwest	26 mph
December 13, 2014	6:30 pm	Northwest	8 mph*
February 5, 2015	6:30 pm	Northwest	18 mph

*Notus Turbine was not operating on this day

With the exception of the initial visit in July 2014, each visit occurred during the nightly shutdown of the Wind #1 and Wind #2 at 7:00pm. This allowed for a direct comparison of turbine operation and ambient conditions within a 1 hour period. In general, for data presented herein, operational measurements were taken between 6:30pm and 7:00pm while ambient measurements were taken from 7:00pm to 7:30pm, immediately following the shutdown of the turbines. As the July 2014 site visit occurred earlier in the afternoon, ambient measurements were not taken. For the November, December, and February visits, asynchronous infrasonic measurements were taken both within the interior of the Andersen residence and right outside the home. Indoor measurements were taken within the living room while outdoor measurements were taken on the front lawn.

Figures 2-5 present the indoor infrasonic sound pressure levels measured from 0 to 10 Hz for each visit. The graphs for the latter three visits also include the measured outdoor operational and indoor ambient infrasonic sound pressure levels. In each figure, regular discernable tones[4]

[4] The sharp amplitude peaks shown do not strictly meet the requirements for most standardized definitions of a tone, however, for the purposes of this report, they will be referred to as such for brevity.

can be identified to varying degrees between 0.7 and 5 Hz. It was determined that the lowest of these tones, occurring at 0.72 Hz, coincides with the blade pass frequency (BPF) of the Vestas V82 turbine at full rotation speed (as given in the Vestas data sheet, Appendix A). The blade pass frequency is seen in all rotating machinery with blades including fans and propellers and is a function of the machinery rotation speed in revolutions per minute (rpm) and the number of blades. The BPF in hertz is calculated using the following formula:

$$BPF\ (Hz) = \frac{Rotation\ Rate}{60} * [No.of\ blades]$$

For the 3-bladed Vestas V82 turbine rotating at 14.4 rpm, the BPF is:

$$BPF\ (Hz) = \frac{14.4\ rpm}{60} * 3\ blades\ = 0.72\ Hz$$

In addition to the blade pass frequency, rotating bladed machinery produces harmonics of the BPF which occur at integer multiples of the BPF. Table 2 shows the turbine blade pass frequency (1x BPF) and the first seven harmonics (2x – 8x BPF). Each of the frequencies shown in Table 2 was identified during at least one visit and many were found during all operational measurements.

Table 2: Calculated Blade Pass Frequency Harmonics

	1x BPF	2x BPF	3x BPF	4x BPF	5x BPF	6x BPF	7x BPF	8x BPF
Freq. (Hz)	0.72	1.44	2.16	2.88	3.60	4.32	5.04	5.76

Of note in Figures 3-5, while these tones are clearly identified in the operational indoor measurements, they are completely absent from the ambient indoor measurements following the shutdown of the turbines. Clear identification of these tones is less consistent in the outdoor measurements due to higher overall broadband infrasonic noise, likely due to wind which is not found for measurements taken indoors.

Examination of the data with the two Town wind turbines shut down shows no indication of any residual infrasound inside the home. This would be the case if the Notus Wind turbine had any impact at the Andersen residence. It should be noted, that the differences between the infrasonic measurements with the wind turbines secured and with the Wind #1 and Wind #2 operating are much greater than 6 dB.

Figure 6 is a compilation of the measured indoor infrasound from the four visits. This graph shows that the tones associated with the BPF and its harmonics occur at consistent frequencies over the span of the four visits. Further, with this figure, the substantial variations in amplitude between the visits can be more easily seen and explanations for this variation can be theorized. Note that the highest measured levels for these tones were taken during the July visit during a moderate (17 mph) downwind condition while the lowest levels were taken during the December measurements during a low (8 mph) downwind condition. While substantially lower in absolute amplitude, the December measurements have a similar peak-to-trough difference (10+ dB) from the tones to the frequencies between the tones suggesting, even within the house, the wind controls the ambient broadband infrasonic sound level. Finally, measurements performed in November show both high broadband levels and lower peak-to-trough differences suggesting high wind speed and/or an upwind wind direction partially obscure the clearly identifiable wind turbine infrasonic signature.

Historically, when the wind turbine sound is particularly bothersome, Mrs. Andersen has reportedly sought refuse in the dining room which is located in the back of the home. NCE understands that at times she has used this room as a second “bedroom”. NCE tested this room and found a lower level of infrasound in the 4 to 7 Hertz range as shown in Figure 7. NCE does not have any explanation why this room has lower infrasound only at these frequencies, but her actions are consistent with these test results.

6.0 CONCLUSIONS

The methods used herein allowed for the collection of infrasonic sound pressure levels within the inside of the Andersen residence. As shown in Figure 6, there is a readily identifiable acoustic signature that can be definitively attributable to Wind #1 and possibly Wind #2 located outside the Andersen home. To NCE’s knowledge, this is the first time such measurements have been performed and reported with respect to the Falmouth wind turbines. However, this is not the first time such measurements have been performed, and other researchers have collected low frequency infrasonic acoustic signatures at other wind turbine sites in Wisconsin and Australia (references 11, 12). As reported in these other studies, the same blade passage rate infrasound and harmonic shown inside the Andersen home have been identified.

Given NCE’s signature analysis and the dramatic change in this acoustic signature when the wind turbine(s) are shut down, NCE can unequivocally state that the infrasonic signature captured inside the Andersen residence is 100% attributable to either one or both of the Town of Falmouth Wind Turbines. To put the conclusions more commonly, this study finds that the wind turbine(s) produce acoustic emissions which are “acoustically trespassing” into the Andersen home.

REFERENCES

1. Noise Control Engineering, Inc. presentation, “Evaluation of Noise Data from WIND-1 Turbine Falmouth, Massachusetts, (via PowerPoint), dated September 27, 2010.
2. Town of Falmouth Code, Article XXXIV Windmills, §240-166, Special Permit Required, Criteria, dated September 1, 2007. (Superseded in July 2013, but it was applicable when reference [1] was originally presented).
3. Commonwealth of Massachusetts, Executive Office of Environmental Affairs, Division of Air Quality Control, DAQC Policy #90-001, dated February 1, 1990.
4. Harris Miller Miller Hanson Report No. 304390 “Falmouth Wind Turbine Noise Study,” dated September 2010.
5. Harris Miller Miller Hanson Technical Memorandum, “Addendum to HMMH Report No. 304390 Falmouth Wind Turbine Noise Study,” dated April 1, 2011.
6. Epsilon Associates letter to Mr. Daniel Web, “Noise Compliance testing on December 10, 2010, Notus Clean Energy Wind Turbine, Falmouth, MA, dated January 6, 2011.
7. Decision of the Town of Falmouth Zoning Board of Appeals, Special Permit 19-08, Applicant Float Realty Trust, Douglas Chester Webb, Trustee and Notus Clean Energy, LLC dated July 31, 2008.
8. Massachusetts Department of Environmental Protection report, “Attended Sampling of Sound from Wind Turbine #1, Falmouth, Massachusetts”, dated May 2012.
9. Massachusetts Department of Environmental Protection report, “Attended Sampling of Sound from Wind Turbine #1 and Wind Turbine #2 – Daytime Operation, Falmouth, Massachusetts (Part 2)”, dated November 2012.
10. Commonwealth of Massachusetts, Superior Court Civil Action No. BACV2013-00281, Town of Falmouth vs. Town of Falmouth Zoning Board of Appeals & others, Memorandum of Decision and Oder on Defendants’ Motion for Preliminary Injunction, /signed/ Christopher J. Muse, Justice of the Superior Court, dated November 21, 2013.
11. James, Richard Sound Pressure Level (SPL) Measurements of Infrasound Inside Homes and Proximate to the Footprint of The Shirley Wind Project (Duke Energy), dated August 9, 2014.
12. Hansen, Kristy, Branko Zajamsek, and Colin Hansen, “Analysis of Unweighted Low Frequency Noise and Infrasound Measured at a Residence in the Vicinity of a Wind Farm”, Australian Acoustical Society, Proceedings of Acoustics 2013 – Victor Harbor, dated November 2013.

FIGURE 1: Location of Andersen Residence relative to Wind #1, Wind #2 and Notus wind turbines.

FIGURE 2

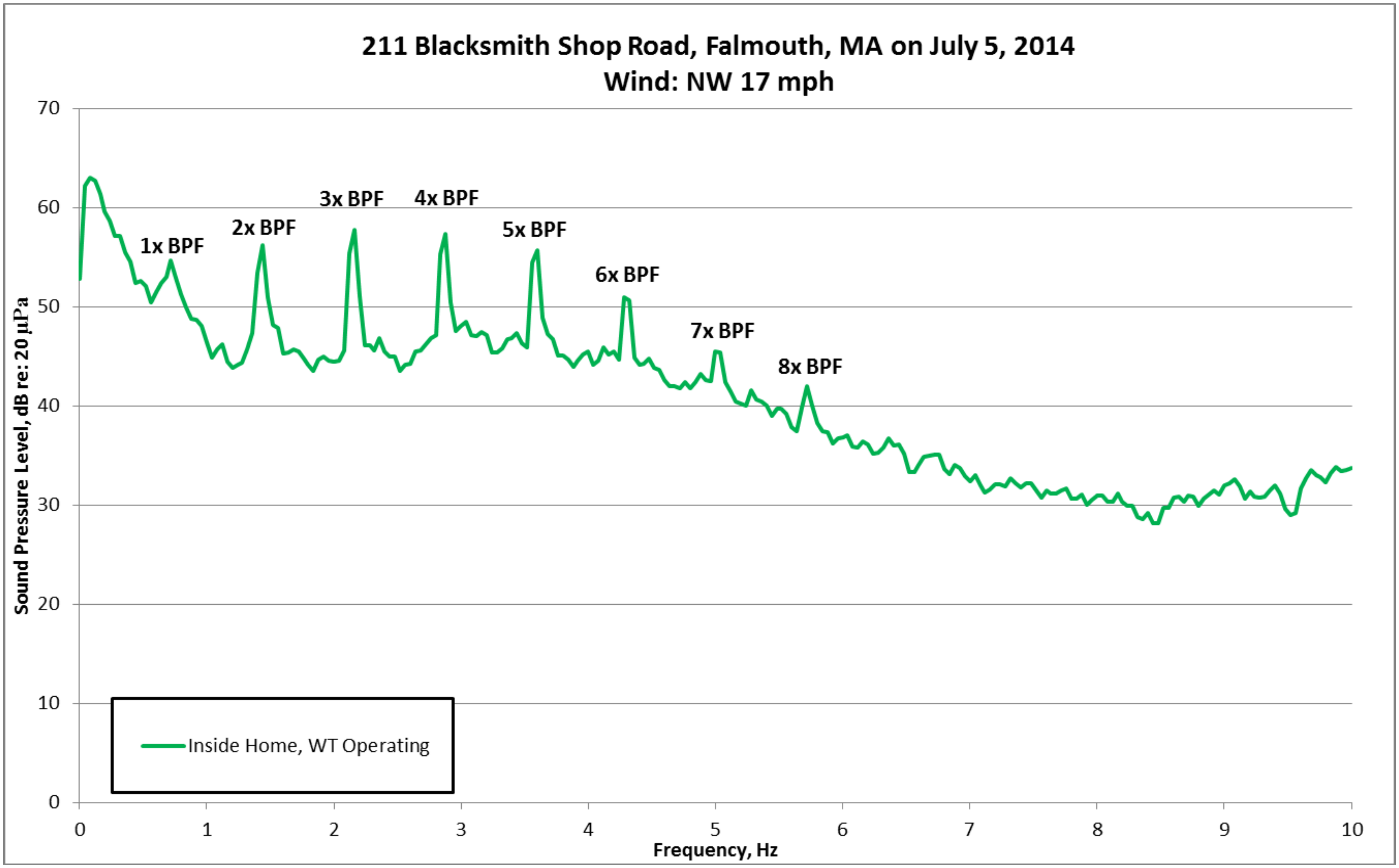

211 Blacksmith Shop Road, Falmouth, MA on July 5, 2014
Wind: NW 17 mph
Sound Pressure Level, dB re: 20 µPa
Frequency, Hz
1x BPF
2x BPF
3x BPF
4x BPF
5x BPF
6x BPF
7x BPF
8x BPF
Inside Home, WT Operating
0
10
20
30
40
50
60
70
0
1
2
3
4
5
6
7
8
9
10

FIGURE 3

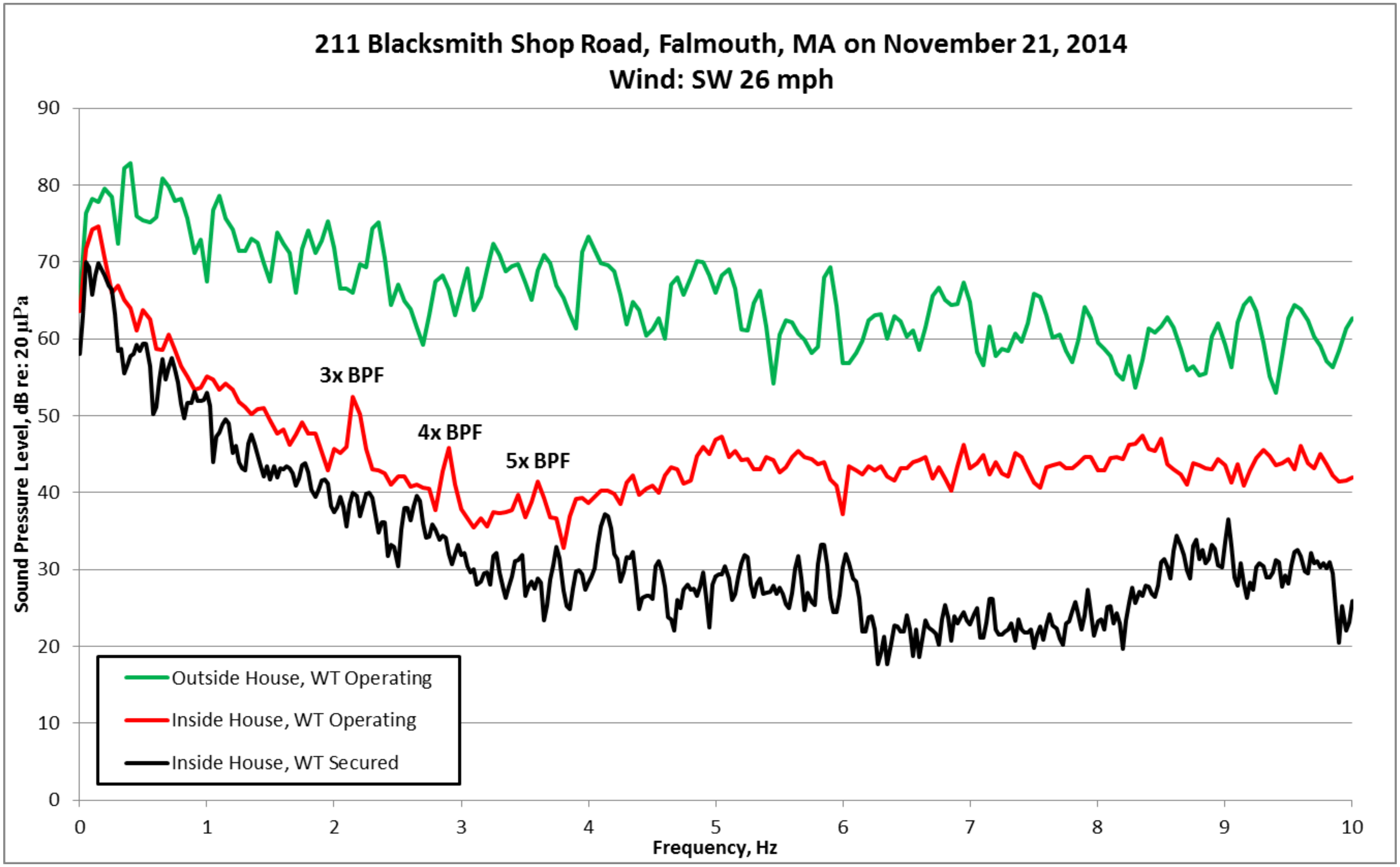

211 Blacksmith Shop Road, Falmouth, MA on November 21, 2014
Wind: SW 26 mph
Sound Pressure Level, dB re: 20 µPa
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
Frequency, Hz
3x BPF
4x BPF
5x BPF
Outside House, WT Operating
Inside House, WT Operating
Inside House, WT Secured

FIGURE 4

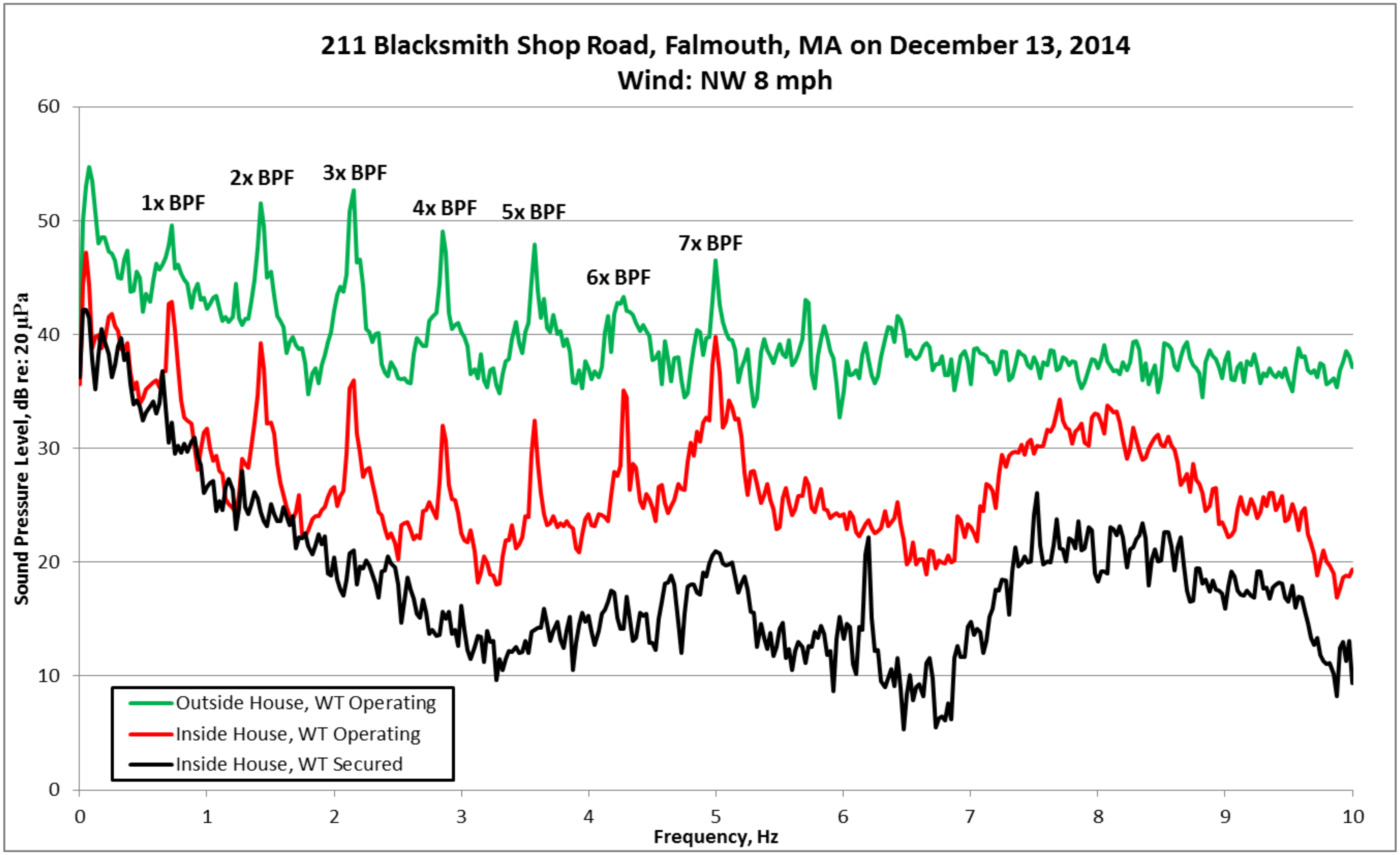

211 Blacksmith Shop Road, Falmouth, MA on December 13, 2014
Wind: NW 8 mph
Sound Pressure Level, dB re: 20 µPa
Frequency, Hz
1x BPF
2x BPF
3x BPF
4x BPF
5x BPF
6x BPF
7x BPF
Outside House, WT Operating
Inside House, WT Operating
Inside House, WT Secured
0
10
20
30
40
50
60
0
1
2
3
4
5
6
7
8
9
10

FIGURE 5

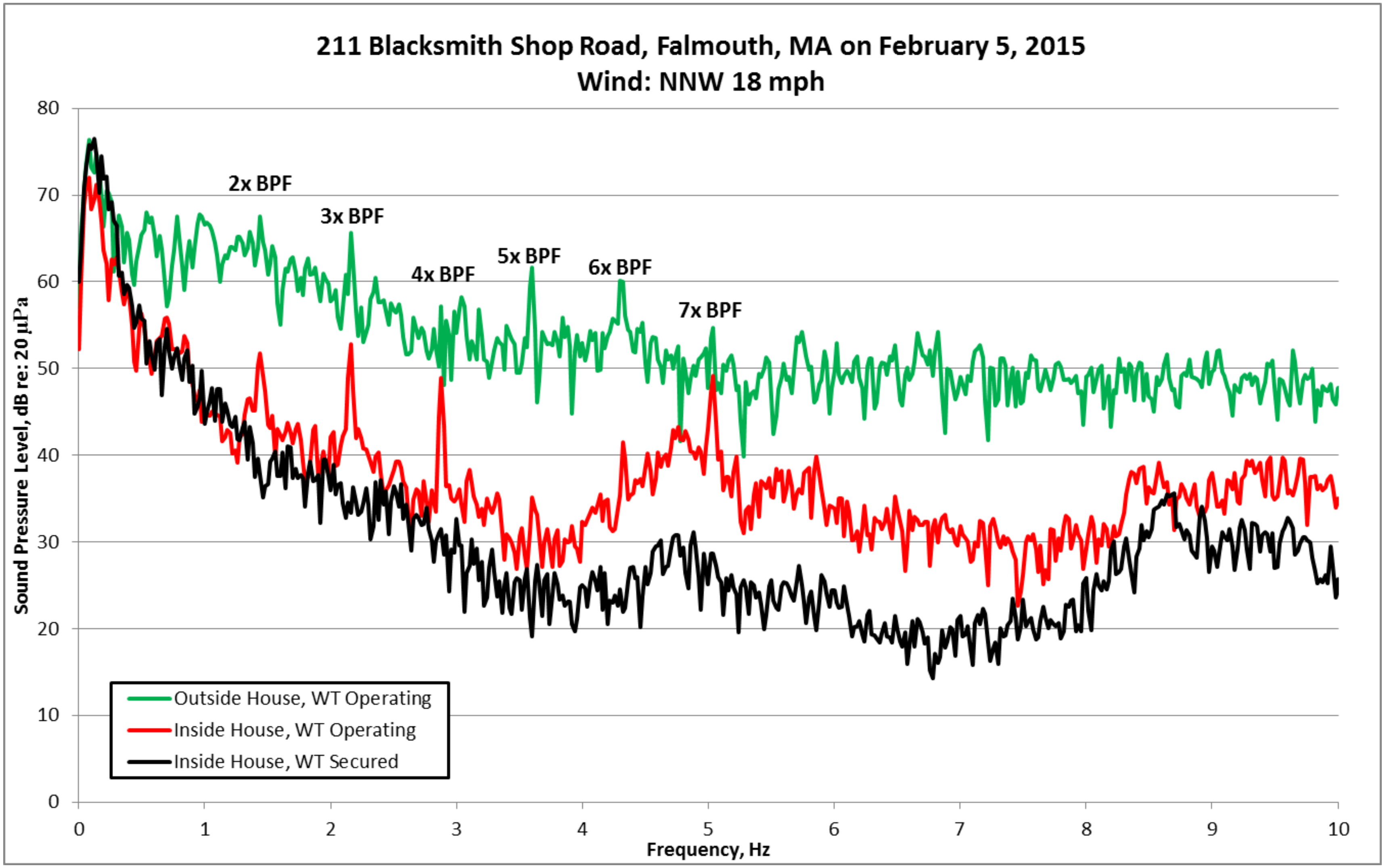

211 Blacksmith Shop Road, Falmouth, MA on February 5, 2015
Wind: NNW 18 mph
2x BPF
3x BPF
4x BPF
5x BPF
6x BPF
7x BPF
Sound Pressure Level, dB re: 20 µPa
Frequency, Hz
0
10
20
30
40
50
60
70
80
1
2
3
4
5
6
7
8
9
Outside House, WT Operating
Inside House, WT Operating
Inside House, WT Secured

FIGURE 6

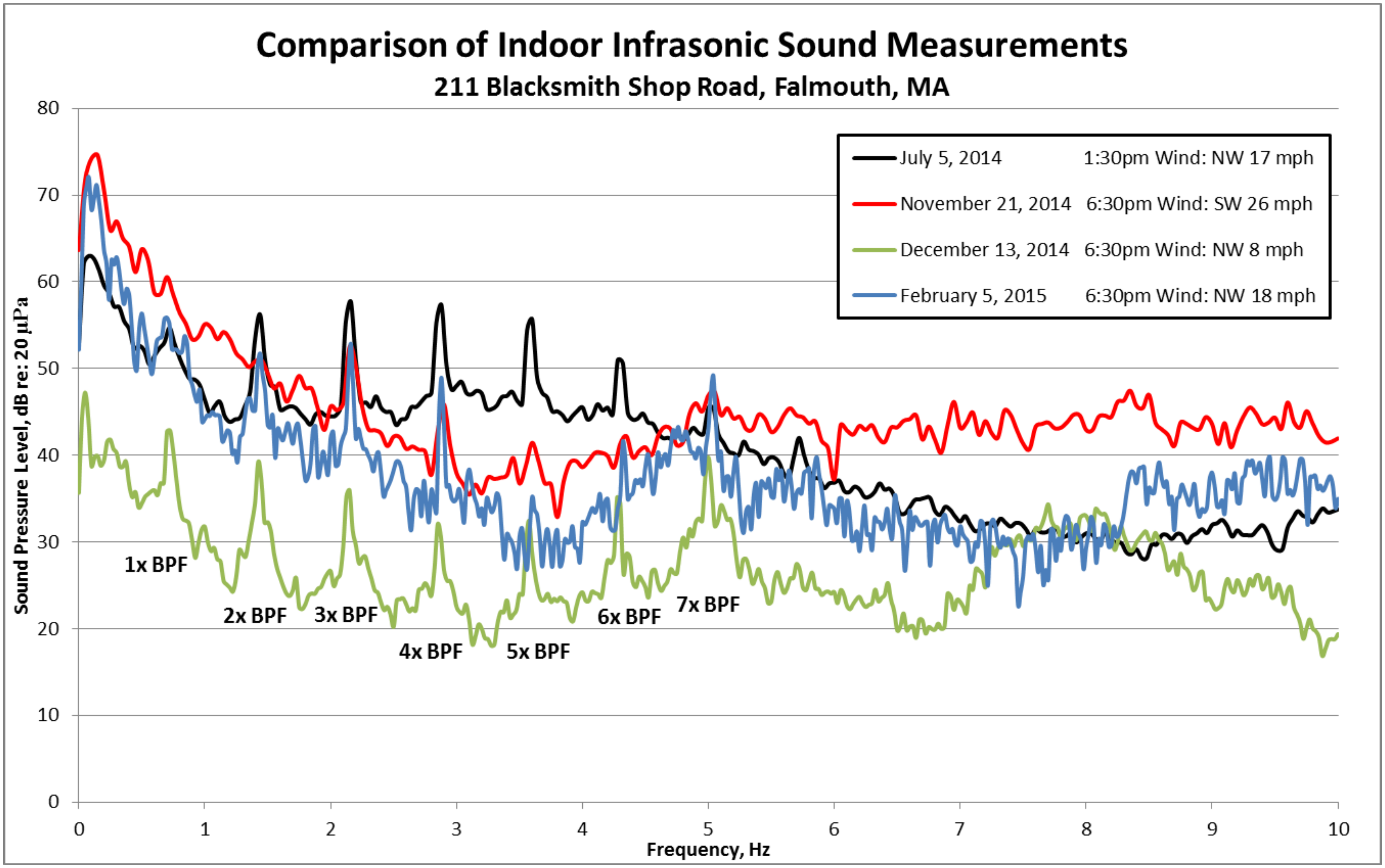
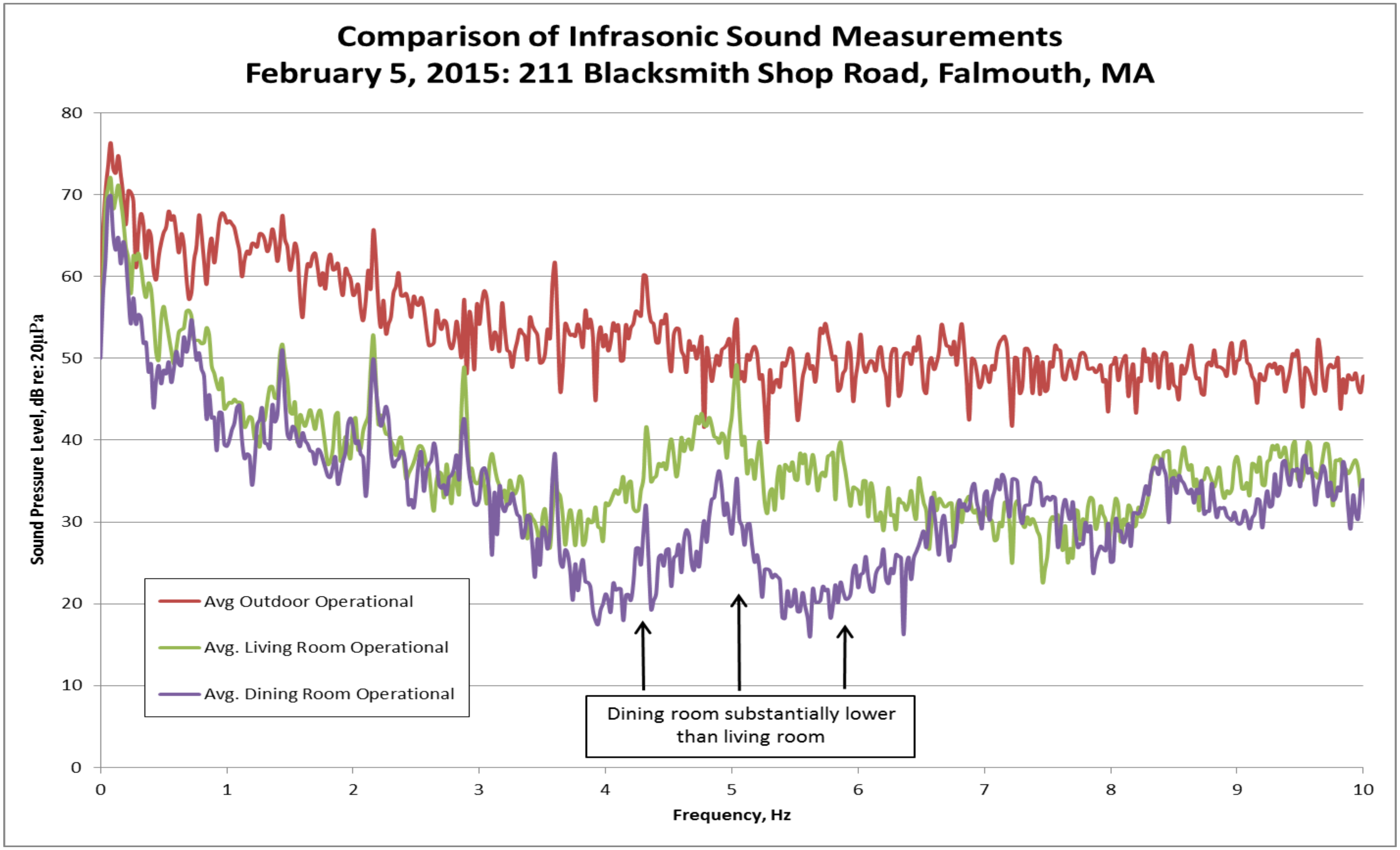

Comparison of Indoor Infrasonic Sound Measurements
211 Blacksmith Shop Road, Falmouth, MA
July 5, 2014 1:30pm Wind: NW 17 mph
November 21, 2014 6:30pm Wind: SW 26 mph
December 13, 2014 6:30pm Wind: NW 8 mph
February 5, 2015 6:30pm Wind: NW 18 mph
1x BPF
2x BPF
3x BPF
4x BPF
5x BPF
6x BPF
7x BPF
Sound Pressure Level, dB re: 20 µPa
Frequency, Hz
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10

FIGURE 7


Comparison of Infrasonic Sound Measurements
February 5, 2015: 211 Blacksmith Shop Road, Falmouth, MA
Sound Pressure Level, dB re: 20µPa
Frequency, Hz
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6
7
8
9
10
Avg Outdoor Operational
Avg. Living Room Operational
Avg. Dining Room Operational
Dining room substantially lower than living room

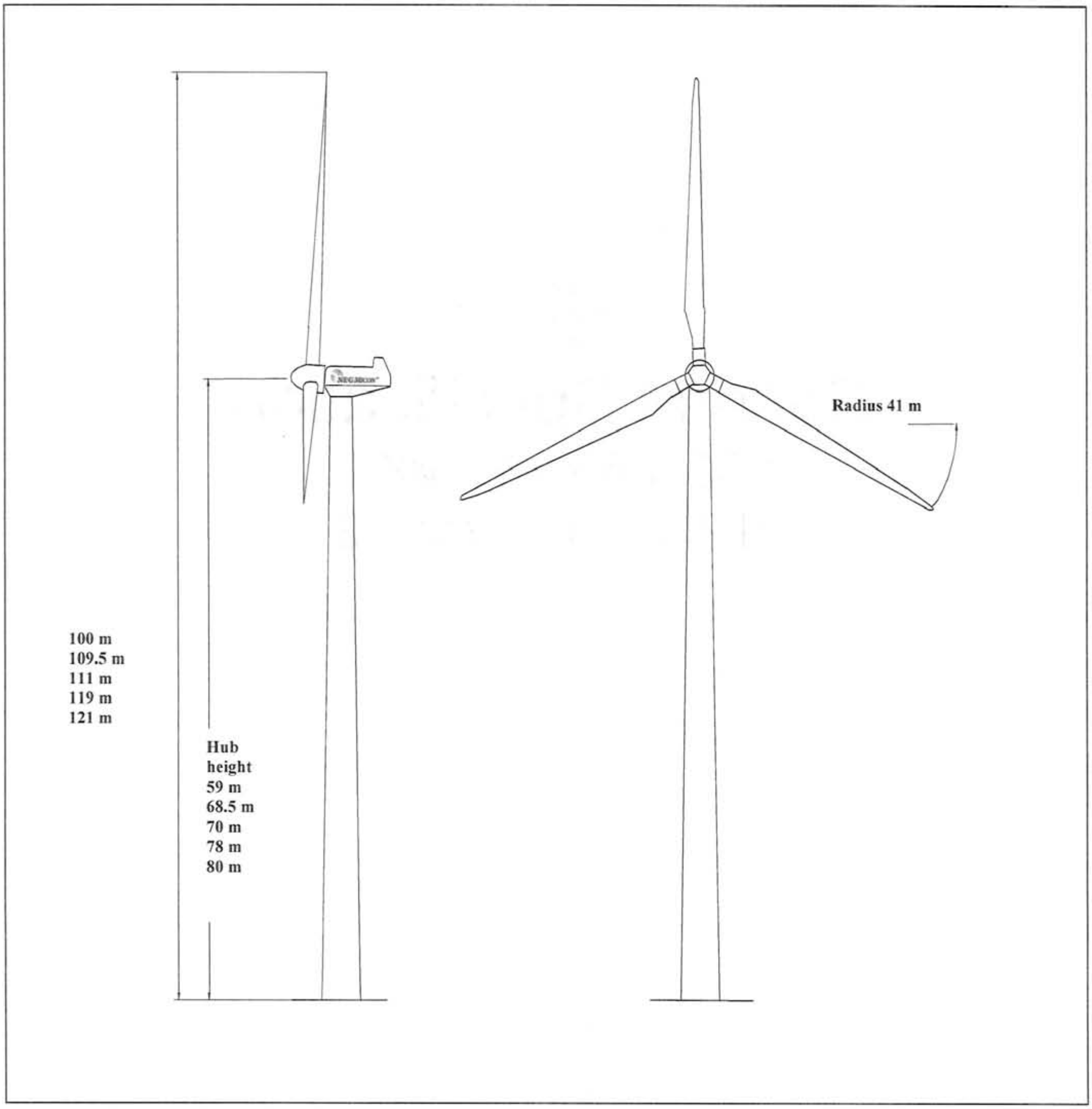
APPENDIX A

Vestas Model V82
Wind Turbine Data Sheet

Class I
TSD 4000258-02 EN
2005-02-09

General Specification
V82-1.65 MW MK II
NM82/1650 Vers. 2

0	Illustration


100 m
109.5 m
111 m
119 m
121 m
Hub
height
59 m
68.5 m
70 m
78 m
80 m
Radius 41 m

1	Main Data			
		50 Hz	**60 Hz**	**60 Hz UL**
	Nominal Power	1650 kW	1650 kW	1650 kW
	Rotor diameter	82 m	82 m	82 m
	Swept area	5281 m^2	5281 m^2	5281 m^2
	Hub height. IEC IIb	59 m, 68.5 m, 70 m, 78 m	70 m, 78 m.	59 m, 70 m, 80 m
	Rotational speed	14.4 rpm	14.4 rpm	14.4 rpm

2	Nacelle Base Frame		
		50Hz	**60Hz**
	Material	EN-GJS-400-18U-LT	EN-GJS-400-18U-LT
	Standard colour	RAL 7035	RAL 7035
	Corrosion class, outside	Acc. to DS EN ISO 12944:C5 I	Acc. to DS EN ISO 12944:C5 I

3	Rotor		
		50Hz	**60Hz**
	Number of blades	3 pieces	3 pieces
	Tip speed (synchronous)	61.8 m/s	61.8 m/s
	Rotor shaft tilt	5°	5°
	Eccentricity (tower center to hub center)	3447 mm	3447 mm
	Solidity (Total blade area/rotor area)	5.0 %	5.0 %
	Power regulation	Active Stall®	Active Stall®
	Rotor orientation	Upwind	Upwind

4	Blades		
		50Hz	**60Hz**
	Type description	AL 40	AL 40
	Blade length	40 m	40 m
	Material	Carbon/wood/glass/epoxy	Carbon/wood/glass/epoxy
	Standard colour	RAL 7035	RAL 7035
	Gloss	Class 2: (30-70%) in accordance with (1), to be measured acc. to DS/ISO2813	Class 2: (30-70%) in accordance with (1), to be measured acc. to DS/ISO2813
	Type of rotor air brake	Full blade	Full blade
	Blade profiles	• FFA -W3, NACA 63.4	• FFA - W3, NACA 63.4
	Twist	20°	20°
	Largest chord	3.08 m	3.08 m
	Blade area (projected)	86 m^2	86 m^2
	Note! (1) Technical Criteria for Danish Approval Scheme for Wind Turbines		

5	Blade bearing		
		50 Hz	**60 Hz**
	Type description	Ball bearing	Ball bearing
	Number of bearings	3 pcs.	3 pcs.

6	Hub		
		50Hz	**60Hz**
	Type description	Spherical	Spherical
	Material	EN-GJS-400-18U-LT	EN-GJS-400-18U-LT
	Corrosion class, outside	Acc. to DS EN ISO 12944:C5 I	Acc. to DS EN ISO 12944:C5 I

7	Main shaft		
		50Hz	**60Hz**
	Type description	Forged shaft and flange	Forged shaft and flange
	Material	34CrNiMo6 + QT	34CrNiMo6 + QT
	Corrosion class	Acc. to DS EN ISO 12944:C2	Acc. to DS EN ISO 12944:C2

8	Main Bearing		
		50Hz	**60Hz**
	Type description	Spherical roller bearing	Spherical roller bearing
	Number of	1 piece	1 piece
	Lubrication	Oil pump	Oil pump

9	Main Bearing Housing		
		50Hz	**60Hz**
	Type description	Flange bearing	Flange bearing
	Material	EN-GJS-400-18U-LT	EN-GJS-400-18U-LT

10	Gearbox		
		50 Hz	**60Hz**
	Type description	1. step planet, 2. step helical	1. step planet, 2. step helical
	Gear house material	Cast	Cast
	Ratio	1:70.2	1:84.3
	Mechanical power	1800 kW	1800 kW
	Bending strength acc. to ISO 6336	$S_F > 1.6$	$S_F > 1.6$
	Surface durability acc. to ISO 6336	$S_H > 1.25$	$S_H > 1.25$
	Scuffing safety acc. to DNV 41.2	$S_S > 1.3$	$S_S > 1.3$
	Shaft seals	Labyrinth	Labyrinth
	Oil sump	App. 250 l	App. 250 l

11	Cartridge Gear Heater - for Arctic Version only		
		50 Hz	**60 Hz**
	Rating	800 W/ pcs.	800 W/ pcs.
	Number of	4 pieces	4 pieces

12	Oil pump		
		50 Hz	**60Hz**
	Voltage	3 x 690 V	3 x 480 V

13	Heat Exchange Unit (Water/Oil)		
		50 Hz	**60 Hz**
	Cooling capacity	41.3 kW	41.3 kW

14	Oil Cooler		
		50 Hz	**60 Hz**
	Cooling capacity	37.5 kW	37.5 kW

15	Water Pump		
		50 Hz	**60Hz**
	Voltage	1 x 230 V	3 x 480 V

16	Water Cooler/ Radiator		
		50 Hz	**60 Hz**
	Cooling capacity	46.2 kW	46.2 kW

17	Electrical Nacelle Heater - for Arctic Version only		
		50 Hz	**60Hz**
	Voltage	3 x 690 V	3 x 600 V
	Power	20 kW	20 kW
	Number of heaters	2 pieces	2 pieces

18	Mechanical Shaft Brake		
		50 Hz	**60Hz**
	Type description	Active Brake	Active Brake
	Brake disc	Steel, mounted on high speed shaft	Steel, mounted on high speed shaft
	Number of calipers	2 piece	2 piece

19	Hydraulic Power Unit for Mechanical Shaft Brake		
		50 Hz	**60Hz**
	Voltage	3 x 690 V	3 x 480 V
	Working pressure range	140-150 bar	140-150 bar
	Oil capacity	11 l	11 l

20	Coupling		
		50 Hz	**60Hz**
	Type description	Flexible coupling, constant rpm	Flexible coupling, constant rpm

21	Generator			
			50 Hz	60 Hz
	Type description		1 speed generator, water cooled	1 speed generator, water cooled
	Rated power	P_N	1650 kW	1650 kW
	Apparent power	S_N	1805 kVA	1808 kVA
	Rated current	I_N	1510 A	1740 A
	Max power at Class F	P_{Fmax}	1815 kW	1815 kW
	Max current at Class F	I_{Fmax}	1661 A	1914 A
	No load current	I_0	400 A	430 A
	Reactive power consumption at rated power (tolerance. acc to IEC 60034-1)	Q_N	731 kvar	740 kvar
	Reactive power consumption at no load (tolerance. acc to IEC 60034-1)	Q_0	478 kvar	447 kvar
	Number of poles	P	6	6
	Synchronous rotation speed	n_0	1000 rpm	1200 rpm
	Rotation speed at rated power	n_N	1012 rpm	1214 rpm
	Slip at rated power	s_N	1.20 %	1.17 %
	Voltage	U_N	3 x 690 V	3 x 600 V
	Frequency	F	50 Hz	60 Hz
	Coupling		Δ	Δ
	Enclosure		IP54	IP54
	Insulation class/ Temperature increase		F/B	F/B

22	Yaw System – Ball Bearing Slewing Ring		
		50 Hz	60 Hz
	Type description	Ball bearing, internal gearing	Ball bearing, internal gearing

23	Yaw System – Yaw Gear and Motors		
		50 Hz	60 Hz
	Type description	Planetary gear motor	Planetary gear motor
	Gear ratio of yaw gear unit	app. 1:1687	app. 1:1687
	Voltage	3 x 690 V	3 x 480 V
	Rotational speed at full load	920 rpm	1140 rpm
	Number of yaw gears	6 pieces	6 pieces

24	Yaw System – Yaw Brake		
		50 Hz	60 Hz
	Type Description	Hydraulic disc brake	Hydraulic disc brake
	Number of Yaw Friction Units	6 pieces	6 pieces

25	Hydraulic Power Unit for Yaw Brake		
		50 Hz	60 Hz
	Voltage	3 x 400/ 3x 690 V	3 x 480 V
	Working pressure range	140-150 bar	140-150 bar
	Oil capacity	App. 10 l.	App. 10 l.

26	Tower		
		50 Hz	60 Hz
	Type Description	Conical, tubular	Conical, tubular
	Material	Welded steel plate	Welded steel plate
	Corrosion class, outside	Acc. to DS EN ISO 12944: C5 I	Acc. to DS EN ISO 12944: C5 I
	Colour	RAL 7035	RAL 7035
	Access conditions	Internal, safety harness, ladder cage	Internal, safety harness, ladder cage

27	Wind Turbine Main Panel/ Control panel/ phase comp. panel		
		50 Hz	**60 Hz**
	Voltage	3 x 690 V	3 x 600 V
	Frequency	50 Hz	60 Hz
	Cut-in system	Soft with thyristors	Soft with thyristors
	Design Standard	IEC	UL

28	Electrical Grid Requirements		
		50 Hz	**60Hz**
	Max. voltage	+10 % (60 sec.)	+10 % (60 sec.)
	Min. voltage	-10 % (60 sec.)	-10 % (60 sec.)
	Max. voltage	+12.5 % (0.1 sec.)	+12.5 % (0.1 sec.)
	Min. voltage	-15 % (0.1 sec.)	-15 % (0.1 sec.)
	High frequency	+1 Hz (0.2 sec.)	+1 Hz (0.2 sec.)
	Low frequency	- 2 Hz (0.2 sec.)	- 2 Hz (0.2 sec.)
	Maximum asymmetri current	15 % (60 sec.) – phase to ground	15 % (60 sec.) – phase to ground
	Maximum asymmetri voltage	2 % (60 sec.) – phase to ground	2 % (60 sec.) – phase to ground
	Maximum short circuit current	25 kA at 690V	30 kA at 600V
	Single harmonic	Max 1% of any single harmonic	Max 1% of any single harmonic
	Total harmonic distortion	Max 3% total harmonic distortion	Max 3% total harmonic distortion
	Connection	• Solidly grounded wye at secondary (690 V) side of transformer	• Solidly grounded wye at secondary (600 V) side of transformer

29	Integrated Grid Connection System, IGC System, Transformer in tower - Optional (IGC is not delivered in the US)		
	Power Transformer incl. Metal Enclosure		
		50 Hz	60 Hz
	Type description	Cast Resin (dry type)	Cast Resin (dry type)
	Apparent power	1800 kVA	1800 kVA
	Primary voltage	10 – 24 kV+/- 2 x 2.5 %	10 – 24 kV+/- 2 x 2.5 %
	Secondary voltage	0.690 kV	0.600 kV
	Frequency	50 Hz	60 Hz
	Coupling group	Dyn, Solidly grounded wye at 690 V	Dyn, Solidly grounded wye at 600 V
	Switch gear		
	Type description	Gas insulated SF6 ring main unit	Gas insulated SF6 ring main unit
	Nominal voltage	24 kV	24 kV
	Frequency	50 Hz	60 Hz

30a	Power Factor – No Load Compensation - Standard											
	Preconditions											
	Rated power	P_N	1650 kW					1650 kW				
	Rated voltage	U_N	3 x 690V					3 x 600V				
	Frequency	f	50 Hz					60 Hz				
	Reactive power consumption. At rated power (tolerance. Acc to IEC 60034-1)	Q_N	731 kvar					740 kvar				
	Reactive power consumption at no load (tolerance. Acc to IEC 60034-1)	Q_O	478 kvar					447 kvar				
	Capacitor banks:											
	Capacitors		550 kvar, split into steps					499.4 kvar, split into steps				
	Capacitor banks resolution		2 x 25 kvar					2 x 22.7 kvar				
	Min. regulation time (operation)		120 sec.					120 sec.				
	Generator G, 6 poles, 1650 kW:											
	Generator load	%	25	50	75	100	110	25	50	75	100	110
	Power factor without phase compensation (tolerances acc to IEC 60034-1)	cos φ	0.71	0.86	0.91	0.91	0.91	0.69	0.85	0.90	0.91	0.91
	Power factor with phase compensation (tolerances acc to IEC 60034-1)	cos φ	0.99	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98

30b	Power Factor – Full Load Compensation – Optional											
	Preconditions											
	Rated power	P_N	1650 kW					1650 kW				
	Rated voltage	U_N	3 x 690V					3 x 600V				
	Frequency	f	50 Hz					60 Hz				
	Reactive power consumption. At rated power (tolerance. Acc to IEC 60034-1)	Q_N	731 kvar					740 kvar				
	Reactive power consumption at no load (tolerance. Acc to IEC 60034-1)	Q_O	478 kvar					447 kvar				
	Capacitor banks:											
	Capacitors		850 kvar, split into steps					817 kvar, split into steps				
	Capacitor banks resolution		2 x 25 kvar					2 x 22.7 kvar				
	Min. regulation time (operation)		120 sec.					120 sec.				
	Generator G, 6 poles, 1650 kW:											
	Generator load	%	25	50	75	100	110	25	50	75	100	110
	Power factor without phase compensation (tolerances acc to IEC 60034-1)	cos φ	0.71	0.86	0.91	0.91	0.91	0.69	0.85	0.90	0.91	0.91
	Power factor with phase compensation (tolerances acc to IEC 60034-1)	cos φ	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

31	Climate and Site Conditions regarding structural design		
		50 Hz – IEC IIb	**60 Hz – IEC IIb**
	Design life time	20 years	20 years
	Temperature interval for operation	See specifications below	See specifications below
	Temperature interval for structure	See specifications below	See specifications below
	A-factor	9.59 m/s	9.59 m/s
	Form factor, c	2.0	2.0
	Annual average wind speed	8.5 m/s	8.5 m/s
	Wind shear	0.20	0.20
	Extreme wind speed	42.5 m/s (10 min. average)	42.5 m/s (10 min. average)
	Survival wind speed	59.5 m/s (3 sec. average)	59.5 m/s (3 sec. average)
	Automatic stop limit	20 m/s (10 min. average)	20 m/s (10 min. average)
	Automatic stop limit	24 m/s (1 min. average)	24 m/s (1 min. average)
	Automatic stop limit	32 m/s (1 s. average)	32 m/s (1 s. average)
	Re-cut in	18 m/s (10 min. average)	18 m/s (10 min. average)
	Characteristic turbulence intensity acc. to IEC 61400-1 (15 m/s)	16% (including wind farm turbulence)	16% (including wind farm turbulence)
	Air density	1.225 kg/m3	1.225 kg/m3
	Maximum in-flow angle	8°	8°

32	Specific Climate and Site Conditions			
		Standard (only 50 Hz)	**Tropical -20 to +40°C (50 + 60 Hz)**	**Arctic (50 + 60 Hz)**
	Temperature interval for operation[1,2,3]	-20 to +30°C	-20 to +35°C (+40°C)	-30 to +30°C
	Temperature interval for structure	-20 to +50°C	-20 to +50°C	-40 to +50°C

[1] Note! For Tropical! Rated power is reduced to 1500 kW for temperature between +35°C and +40°C.
[2] Note! No operation if temperature is below -10°C in control panel or gear oil sump. Heating systems are optional.
[3] Note! If the windturbine is placed more than 1000m above sea level, a higher temperature rise than usual might occur in the generator, the transformer and other electrical components. In this case a periodic reduction of rated power might occur, even if the ambient temperature is within specified limits. Furthermore increased risk of icing up occur at sites more than 1000m above sea level.

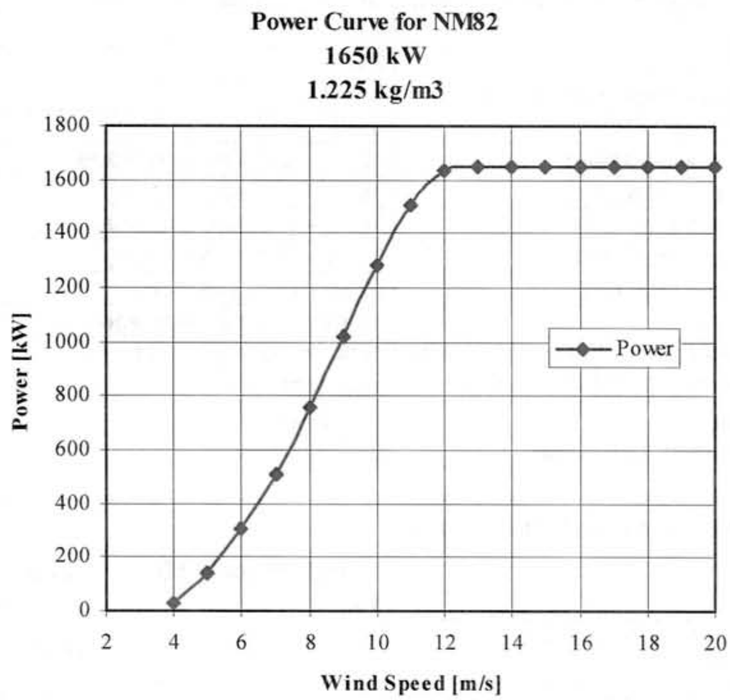
33	**Conditions for Power Curve (at hub height)**		
		50 Hz	**60Hz**
	Air density	1.225 kg/m^3	1.225 kg/m^3
	Wind shear	0.12-0.16	0.12-0.16
	Turbulence intensity	11-16 %	11-16 %
	Blades	Clean	Clean
	Ice/snow on blades	No	No
	Leading Edge	No damage	No damage
	Rain	No	No
	Terrain	IEC 61400-12	IEC 61400-12
	Inflow angle	0±2 °	0±2 °
	Grid frequency	50 ±0.5	60±0.5 Hz
	Verification acc. to	IEC 61400-12	IEC 61400-12

34 Power Curve for Standard Density

The power curve is calculated at air density 1.225 kg/m³

Cut –in wind speed: 3.5 m/s (10 min. average)

Wind speed (m/s)	Power (kW)
3	0
4	28
5	144
6	309
7	511
8	758
9	1017
10	1285
11	1504
12	1637
13	1650
14	1650
15	1650
16	1650
17	1650
18	1650
19	1650
20	1650
>20	0



35 Power Curve

Air density [kg/m³]	0.97	1.00	1.03	1.06	1.09	1.12	1.15	1.18	1.21	1.225	1.24	1.27
Wind speed [m/s]	**Power [kW]**	**Power [kW]**	**Power [kW]**	**Power [kW]**	**Power [kW]**	**Power [kW]**	**Power [kW]**	**Power [kW]**	**Power [kW]**	**Power [kW]**	**Power [kW]**	**Power [kW]**
3	0	0	0	0	0	0	0	0	0	0	0	0
4	15	16	18	19	21	22	24	25	27	28	29	30
5	107	112	116	120	125	129	133	138	142	144	146	151
6	238	246	255	263	271	280	288	296	305	309	313	321
7	399	412	425	438	452	465	478	491	504	511	517	530
8	589	608	627	645	664	683	702	722	746	758	767	788
9	794	818	843	867	892	916	941	968	999	1017	1028	1058
10	995	1025	1055	1085	1116	1147	1178	1217	1260	1285	1299	1333
11	1191	1228	1266	1303	1341	1379	1417	1453	1489	1504	1518	1546
12	1371	1415	1459	1504	1548	1588	1620	1628	1636	1637	1639	1642
13	1520	1569	1616	1637	1642	1643	1645	1646	1647	1650	1650	1650
14	1624	1635	1643	1650	1650	1650	1650	1650	1650	1650	1650	1650
15	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650
16	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650
17	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650
18	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650
19	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650
20	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650	1650

36	Cp											
	Air density [kg/m³]	**0.97**	**1.00**	**1.03**	**1.06**	**1.09**	**1.12**	**1.15**	**1.18**	**1.21**	**1.225**	**1.24**	**1.27**
	Wind speed [m/s]	-	-	-	-	-	-	-	-	-	-	-	-
	3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	4	0.092	0.095	0.103	0.106	0.114	0.116	0.123	0.125	0.132	0.135	0.138	0.140
	5	0.334	0.339	0.341	0.343	0.347	0.349	0.350	0.354	0.356	0.356	0.357	0.360
	6	0.430	0.431	0.434	0.435	0.436	0.438	0.439	0.440	0.442	0.442	0.443	0.443
	7	0.454	0.455	0.456	0.456	0.458	0.458	0.459	0.459	0.460	0.461	0.460	0.461
	8	0.449	0.450	0.450	0.450	0.451	0.451	0.452	0.453	0.456	0.458	0.458	0.459
	9	0.425	0.425	0.425	0.425	0.425	0.425	0.425	0.426	0.429	0.431	0.431	0.433
	10	0.388	0.388	0.388	0.388	0.388	0.388	0.388	0.391	0.394	0.397	0.397	0.398
	11	0.349	0.349	0.350	0.350	0.350	0.350	0.351	0.350	0.350	0.349	0.348	0.346
	12	0.310	0.310	0.310	0.311	0.311	0.311	0.309	0.302	0.296	0.293	0.290	0.283
	13	0.270	0.270	0.270	0.266	0.260	0.253	0.247	0.240	0.235	0.232	0.229	0.224
	14	0.231	0.226	0.220	0.215	0.209	0.203	0.198	0.193	0.188	0.186	0.184	0.179
	15	0.191	0.185	0.180	0.175	0.170	0.165	0.161	0.157	0.153	0.151	0.149	0.146
	16	0.157	0.153	0.148	0.144	0.140	0.136	0.133	0.129	0.126	0.125	0.123	0.120
	17	0.131	0.127	0.123	0.120	0.117	0.114	0.111	0.108	0.105	0.104	0.103	0.100
	18	0.110	0.107	0.104	0.101	0.098	0.096	0.093	0.091	0.089	0.087	0.086	0.084
	19	0.094	0.091	0.088	0.086	0.084	0.081	0.079	0.077	0.075	0.074	0.073	0.072
	20	0.081	0.078	0.076	0.074	0.072	0.070	0.068	0.066	0.065	0.064	0.063	0.062

37	Ct											
	Air density [kg/m³]	**0.97**	**1.00**	**1.03**	**1.06**	**1.09**	**1.12**	**1.15**	**1.18**	**1.21**	**1.225**	**1.24**	**1.27**
	Wind speed [m/s]	-	-	-	-	-	-	-	-	-	-	-	-
	3	0.979	0.979	0.979	0.979	0.979	0.979	0.979	0.979	0.979	0.979	0.979	0.979
	4	1.105	1.106	1.107	1.108	1.108	1.109	1.110	1.110	1.111	1.111	1.112	1.112
	5	1.007	1.007	1.008	1.008	1.009	1.009	1.010	1.010	1.010	1.014	1.011	1.011
	6	0.922	0.922	0.923	0.923	0.923	0.924	0.924	0.924	0.925	0.925	0.925	0.925
	7	0.841	0.841	0.841	0.841	0.842	0.843	0.843	0.843	0.843	0.843	0.843	0.843
	8	0.765	0.765	0.765	0.766	0.766	0.766	0.767	0.767	0.767	0.768	0.768	0.773
	9	0.691	0.692	0.692	0.692	0.692	0.693	0.693	0.693	0.694	0.701	0.697	0.713
	10	0.619	0.620	0.620	0.620	0.621	0.621	0.621	0.621	0.626	0.642	0.634	0.649
	11	0.554	0.555	0.555	0.555	0.555	0.559	0.559	0.567	0.570	0.578	0.578	0.584
	12	0.494	0.494	0.494	0.495	0.495	0.498	0.501	0.506	0.507	0.509	0.509	0.509
	13	0.438	0.438	0.439	0.439	0.440	0.440	0.440	0.439	0.438	0.438	0.437	0.436
	14	0.386	0.386	0.385	0.384	0.383	0.382	0.381	0.380	0.380	0.379	0.379	0.378
	15	0.340	0.339	0.339	0.338	0.337	0.336	0.336	0.335	0.335	0.334	0.334	0.334
	16	0.302	0.302	0.301	0.301	0.300	0.300	0.300	0.300	0.299	0.299	0.299	0.299
	17	0.270	0.270	0.271	0.271	0.271	0.270	0.271	0.271	0.271	0.272	0.272	0.271
	18	0.248	0.248	0.249	0.248	0.249	0.248	0.249	0.249	0.249	0.249	0.250	0.249
	19	0.229	0.229	0.229	0.230	0.230	0.230	0.231	0.231	0.231	0.232	0.233	0.235
	20	0.213	0.213	0.214	0.214	0.215	0.215	0.216	0.216	0.218	0.218	0.218	0.220

38	Guaranteed Sound Power Level at Hub Height					
	Conditions for Sound Power Level:	Wind shear: 0.13 Max turbulence at 10 meter height: 16% Inflow angle (vertical): 0 ± 2° Air density: 1.225 kg/m^3				
	Hub Height	HH 59 m	HH 68.5 m	HH 70 m	HH 78 m	HH 80 m
	Verification Report: WT SE03007 B2					
	L_{wA} @ 3 m/s (10 meters above ground) (dB(A))	100.4	100.4	101.1	101.1	101.1
	L_{wA} @ 4 m/s (10 meters above ground) (dB(A))	100.9	100.9	100.9	101.4	101.4
	L_{wA} @ 5 m/s (10 meters above ground) (dB(A))	101.1	101.1	101.1	101.6	101.6
	L_{wA} @ 6 m/s (10 meters above ground) (dB(A))	101.3	101.3	101.3	101.8	101.8
	L_{wA} @ 7 m/s (10 meters above ground) (dB(A))	101.9	101.9	101.9	102.2	102.2
	L_{wA} @ 8 m/s (10 meters above ground) (dB(A))	102.9	102.9	102.9	103.2	103.2
	L_{wA} @ 9 m/s (10 meters above ground) (dB(A))	103.1	N/A	N/A	N/A	N/A
	L_{wA} @ 95% Rated Power (9.1 m/s. 10 meters above ground) (dB(A))	103.3	N/A	N/A	N/A	N/A
	L_{wA} @ 95% Rated Power (8.9 m/s 10 meters above ground) (dB(A))	N/A	103.3	103.3	103.3	N/A
	L_{wA} @ 95% Rated Power (8.8 m/s 10 meters above ground) (dB(A))	N/A	N/A	N/A	N/A	103.3

The Wind Turbine is designed according to Vestas design specifications.
Vestas Wind Systems A/S reserves the right to change specifications without prior notice.