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Lightning Activities in the DOE-EPRI Turbine Verification Program

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LIGHTNING ACTIVITIES IN THE DOE-EPRI TURBINE VERIFICATION PROGRAM

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Abstract

The U.S. Department of Energy (DOE)-Electric Power Research Institute (EPRI) Turbine Verification Program (TVP) has played a vital role in improving the understanding of lightning protection for wind turbines. In response to concerns from host utilities, the TVP began a lightning protection project to study the impact of lightning activity at the 6.0-megawatt (MW) wind power facility in Ft. Davis, Texas. McNiff Light Industry (MLI) and Global Energy Concepts (GEC) established a broad observation and documentation effort to survey the lightning protection methodologies used and to evaluate the damage resulting from lightning activity at the turbines. The 6.05-MW wind power plant in Searsburg, Vermont, was inspected after a severe lightning storm caused damage to several turbines there. Zond, McNiff, and consultants from Lightning Technologies, Inc. conducted post-damage inspections at both sites to develop recommendations for improving lightning protection. Site operators implemented the recommended mitigation strategies, and the turbines were monitored to determine if the protection measures improved project operations. This paper summarizes the experience gained through TVP's lightning-related research, and provides a set of guidelines for wind turbine manufacturers, owners, and operators.

Introduction

The TVP is a joint effort of DOE, EPRI, and several utilities to evaluate early production models of advanced wind turbines and to verify the performance, reliability, maintainability, and cost of new wind turbine designs and system components in commercial utility environments. GEC and MLI serve as support contractors providing project management guidance, monitoring, reporting, and a variety of technical assistance.

This paper discusses the history of lightning-related incidents at the TVP project sites, the lightning project history, the retrofits, and the lessons learned.

Historical Wind Energy Lightning Risk

The modern era of wind energy development originated in locations where lightning activity is relatively minimal and the risk and frequency of damage to wind turbines is low. In California and Northern Europe, where the majority of the world's wind development occurred before the mid-1990s, lightning is relatively rare. For instance, in Denmark there are on average 10 thunderstorm days per year, and in much of California there are less than 4 annual thunderstorm days. In contrast to these early wind development areas, six out of the seven TVP projects were installed in areas where high lightning activity is indicated by 35 mean annual thunderstorm days. Figures 1 and 2 depict the distribution of thunderstorm and lightning activity in the United States. The stars on the Figure 1 map indicate the TVP sites. Figure 3 presents a more detailed map of the lightning frequency in the area around Big Spring, Texas.

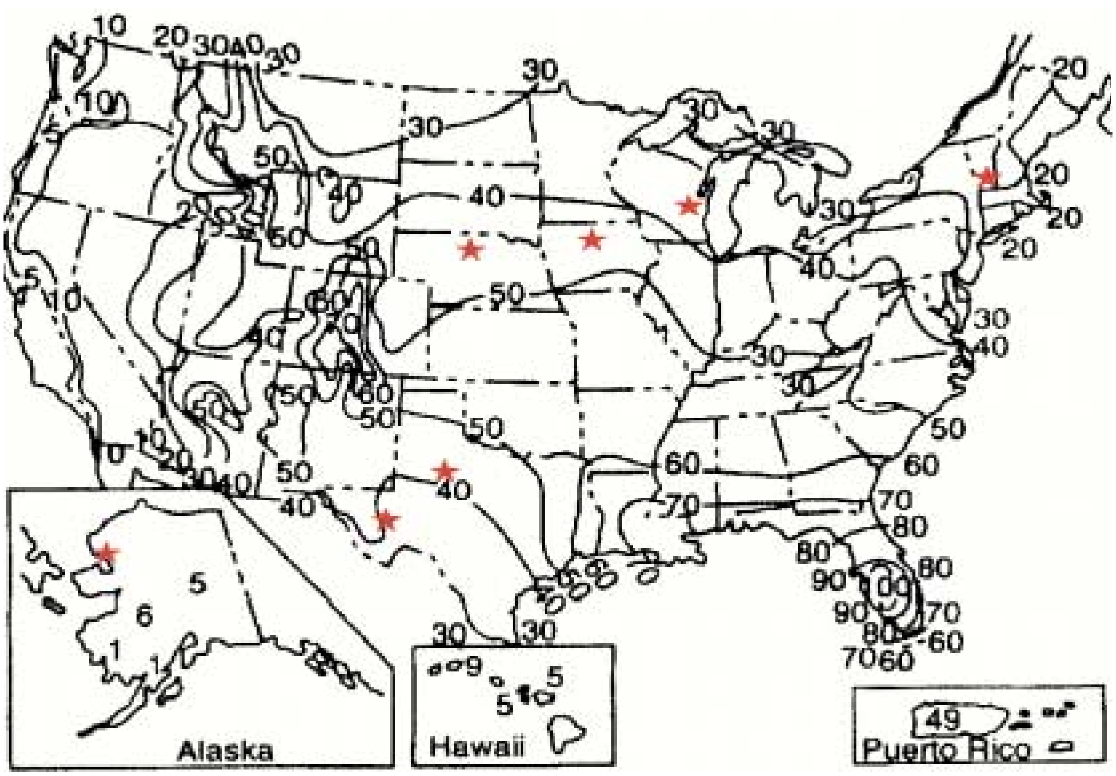

Figure 1. Mean annual thunderstorm days in the United States

Lightning Risk at TVP Wind Sites

Lightning strike risk is a function of thunderstorm frequency and turbine equivalent strike collection area. Table 1 details the lightning risk at the seven TVP wind sites determined from National Weather Service data (80 year database) and reports from Global Atmospherics based on the National Lightning Detection Network database statistics on lightning-strike density (5-8 year database) . As can be seen, the sites in Vermont, the Midwest, and Texas have considerably more thunderstorm activity than the typical California site.

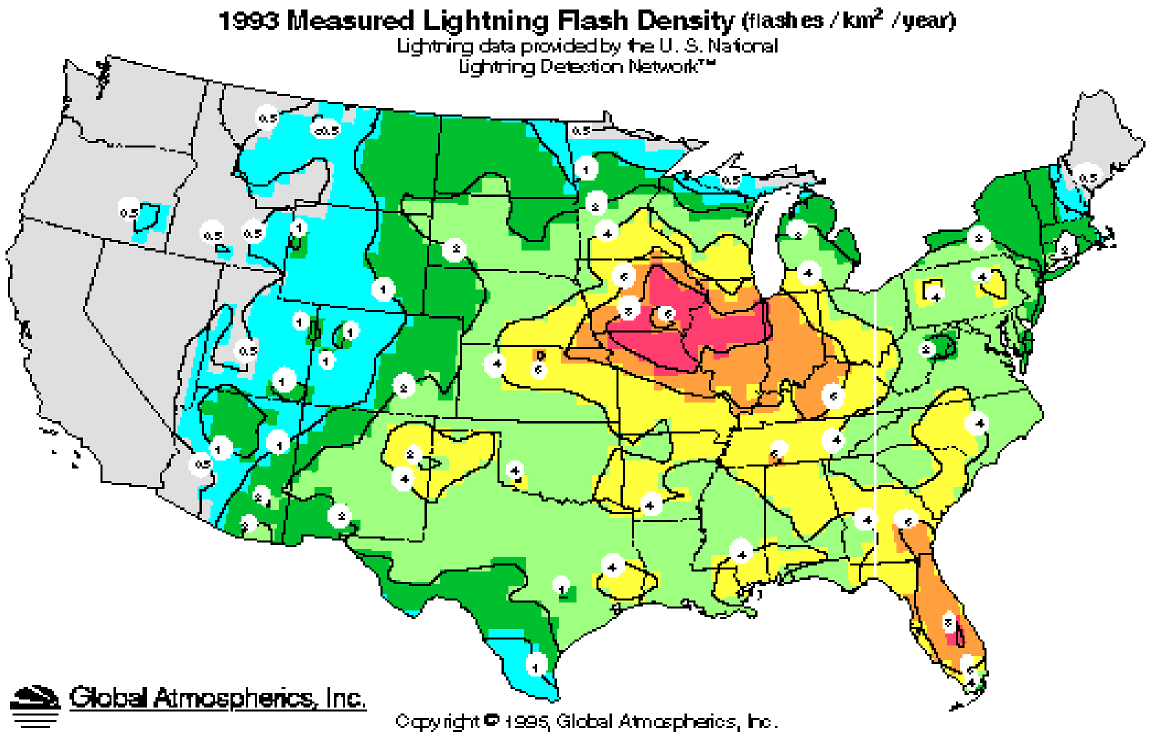

Figure 2. Typical measured lightning flash density in the United States

Table 1. TVP Lightning Strike Risk

Site	Thunderstorm Days/Year	Ground Flash Density (#/km^2)	Strike Collection Area (km^2)	Estimated Turbine Strikes/Year	Est. Average Strikes per Turbine per Year [1]
Ft. Davis, TX	41	3.0	0.65	1.9	0.16
Searsburg, VT	25	1.5	0.57	0.9	0.08
Glenmore, WI	36	1.75	0.30	0.5	0.25
Algona, IA	43	2.5	0.40	1.0	0.33
Springview, NE	44	2.5	0.35	0.9	0.43
Kotzebue, AK	1	<0.2	0.25	<0.05	0.0
Big Spring, TX	40	2.0	4.55	9.1	0.20
Typical CA site [2]	4	0.25	0.16	-	0.04

[1] Estimated Turbine Strikes per year divided by the number of turbines at the site
[2] Based on a single 50-m-diameter rotor with 50-m hub height in Tehachapi

The equivalent strike collection area is the sum of the areas for each wind turbine described by the base of a cone with a radius equal to three times the maximum blade-tip height (or hub-height plus rotor radius). The estimated number of strikes per year is calculated from the flash density and the strike collection area, and the average number of strikes per turbine is based on the number of turbines at the site. It should be noted that the strikes to the site may be attracted to just one or two turbines due to their prominent location. This was observed at the Fort Davis site where 4 of 6 observed strikes taken by Unit 1.

Table 1 shows that the first two TVP projects installed, Ft. Davis and Searsburg, have moderate lightning risk compared to the more recently installed sites in Glenmore, Algona, Springview, and Big Spring. This is mostly due to the higher heights and effective collection areas per turbine. The Wisconsin project has been in operation for more than two years and, although it is in a relatively high-risk area, its lightning problems have been minimal. McNiff theorized that the proximity of three tall communications towers adjacent to the Glenmore site provide a degree of protection to the turbines there. The Algona and Springview projects have been in operation for just over a year, and the Big Spring project came on line in the summer/fall of 1999. These sites have only recently begun to yield data on lightning-associated faults.

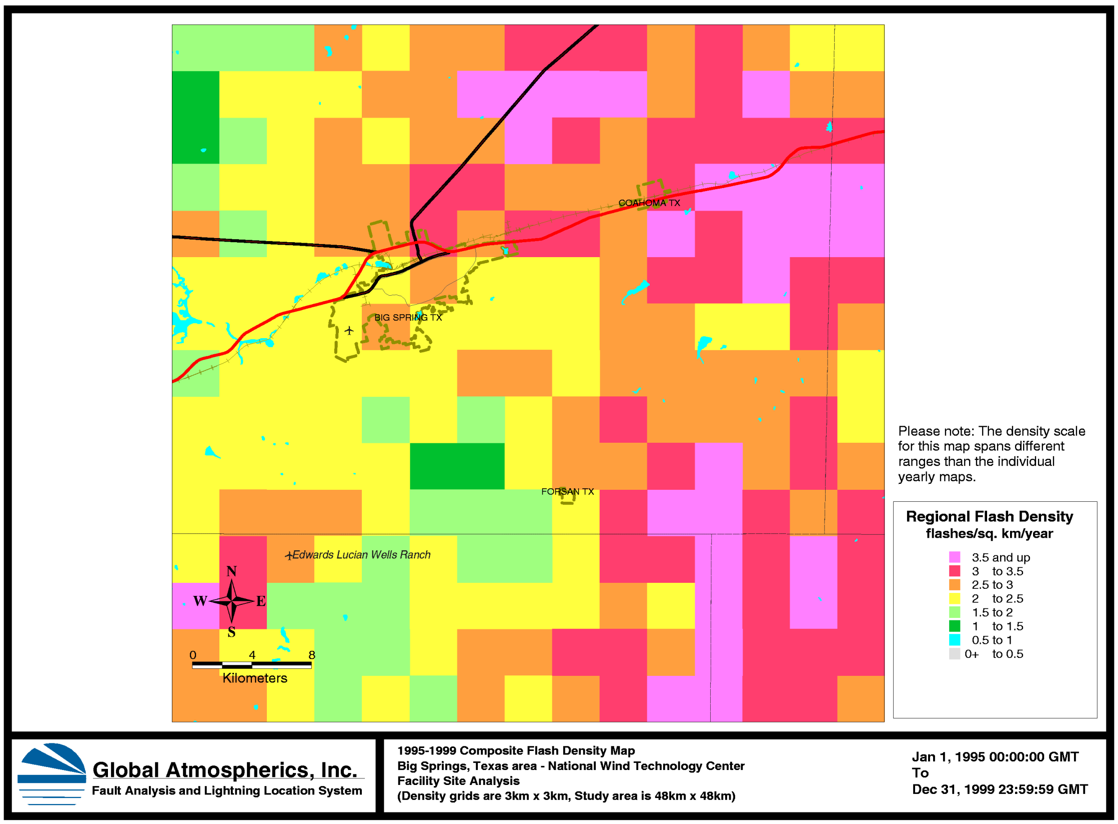

Figure 3. Sample lightning risk report for Big Spring, Texas

TVP Lightning Protection Project

Early operating experience at Ft. Davis revealed the need for better lightning protection because of repeated damage to turbine components during storms. In early 1997, the TVP launched an initiative to study the problem and find solutions, and contracted with MLI to collect additional data, document the damage, and develop recommendations. Figure 4 provides a chronology of major TVP lightning-related events.

TVP Lightning Protection Project Timeline

1996	Ft. Davis, TX first year of operation – considerable damage
January 1997	TVP Lightning Workshop to discuss experiences
July 1997	Lightning activity field-test at Ft. Davis for cause/effect
June 1998	Severe lightning damage at Searsburg, VT
July 1998	LTI & MLI inspected Searsburg damage, made protection recommendations
Sept 1998	LTI & MLI discussed blade and controls protection w/ Zond for Z-40 & Z-50
Spring 1999	Shielding, neutral, and bonding modifications installed at Ft. Davis
July 1999	Wiring modifications installed at Algona, IA
August 1999	Severe blade strike damage at Springview, NE; wiring modifications installed
January 2000	Severe blade strike damage at Searsburg
May 2000	Direct strike to turbine at Ft. Davis with no damage.
June 2000	Blade conductors installed at Algona and Springview

Figure 4. TVP lightning events, 1996–2000

MLI documented lightning strikes and damage at Ft. Davis with a custom data collection system, including video cameras and specially designed strike sensors attached to each tower to record strikes and resultant ground activity. MLI found that significant damage resulted from indirect strikes, and that the turbine controller hardware was the most sensitive. MLI and LTI recommended a series of retrofits to the turbines' grounding and electrical systems, including circuit protection for the turbines' Supervisory Control and Data Acquisition (SCADA) system. Since the improvements were installed, lightning damage to the project has been virtually eliminated.

Based on the experience at Ft. Davis, the TVP recommended lightning protection measures for other projects including grounding the up-tower controller cabinet to the gearbox, terminating shielding on cables, and grounding the lightning rod to the generator case. To obtain additional information, TVP also provided lightning sensors for the Algona, Springview, and Big Spring projects, which tie into the SecondWind System. MLI also modified the tower strike sensors tied into the Second Wind SCADA system for the Algona and Springview TVP projects.

The TVP lightning protection project included site assessments at all TVP locations to evaluate turbine designs and installation approaches with respect to lightning protection. The information was also shared through MLI's participation in international forums and working groups developing the International Electrotechnical Commission (IEC) technical lightning protection standards for wind turbines. Additionally, the information was presented at TVP workshops and AWEA, AIA and ECWEC conferences.

Damage History

The number of lightning events and lightning-related turbine downtime sustained by the Z-40A turbines in Ft. Davis are detailed in Table 2. Downtime is categorized as lightning-related if the event started during or immediately following a documented thunderstorm; if faults or component damage typical of lightning-related events were evident; or if additional information was available to identify lightning as the cause. The data in this table support the observations of the field personnel that the retrofits were successful in reducing lightning damage. Inspection of the damage to one turbine that occurred in June 1999 revealed that installation of the mitigation measures was incomplete in the turbine's nacelle.

Table 2. Ft. Davis Lightning Damage

Period	Lightning Damage Events	Repair Downtime (hrs)	Lightning Faults (suspected)	Lightning Fault Downtime (hrs)	Total Lightning Downtime per Turbine (hrs)
7/96-6/97	12	1800	78	1000	233
7/97-6/98	11	1500	5	76	136
7/98-6/99	5	300	23	129	41

Tables 3 and 4 detail lightning damage to turbines at the various TVP sites during 1999 with summaries of outage time and component damage details, respectively. The repair downtime in Table 3 refers specifically to the time the turbine was down due to lightning damage that required repairsOther faults required a reset only. The majority of the 742 hours of repair downtime at Ft. Davis can be attributed to the failure of two power supplies for which spares were not available on site. The 110 hours of faults (the total of all 12 turbines) was primarily due to lightning causing controller problems at night. No damage was done, but resets were not performed until the following morning.

Table 3. Lightning-Related Faults and Downtime by Site for 1999

Site	Number of Turbines	Repair Downtime (hrs)	Faults (suspected)	Fault Downtime (hrs)	Line Outages (hrs/ turbine)	Total Downtime per Turbine (hrs)
Fort Davis	12	742	1	110	1.5 (+40 suspected)	64 (+49 suspected)
Searsburg	11	449	0	0	16	62
Algona	3	20	14	130	11	16 (+55 suspected)
Springview	2	525	0	0	0	262

The Searsburg project suffered several lightning-related problems in 1999, most of minimal duration, except for extensive damage to a controller on Turbine 1. At Algona, the primary lightning-related problem was a fault condition where noise was generated on the serial communication line between the pitch controller and the main controller. In Springview, a blade was struck by lightning resulting in catastrophic failure, which Zond replaced relatively quickly. At the same time, and on one other occasion, the turbines in Springview suffered damage to the controller and the power electronics matrix, which also took time to repair because spare parts were not available.

The Searsburg site experienced a second blade failure from a direct lightning strike on January 11, 2000, as shown in Figure 5. The Big Spring project was not fully operational until late in 1999 so it is not included in these tables. Also, the Wisconsin turbines did not suffer any appreciable lightning damage or downtime, presumably because of the protection afforded by tall communications towers nearby and good shielding techniques in the turbine controls.

Table 4. Lightning Damage Detail

Project Location	Turbine #	Date of Event	Hours Down	Turbine System	Damage
Fort Davis, TX	12	6/22/99	13.2	Controller	Resistor network protecting SCADA modem
	2	6/22/99	729.0	Controller	Two power supplies in VPC and two pressure transducers; spares not available
Searsburg, VT	9	7/15/99	0.2	Controller	Intermittent SCADA communication
	2	7/16/99	1.5	Controller	Intermittent SCADA communication
	2	7/19/99	3.3	Controller	Intermittent SCADA communication, gas flash-tube lightning arrestor
	7	7/29/99	2.2	Hydraulics	Hydraulic contactor
	9	7/30/99	13.5	Controller	Lan-A1 and two pressure transducers
	1	7/30/99	371.5	Controller	Extensive damage
	10	7/30/99	43.7	Controller	Power supply and input control board #1
	7	7/30/99	12.5	Controller	Replaced SCADA communications card
	11	7/30/99	0.7	Controller	Lan-A1 and SCADA modem
Algona, IA	2	6/9/99	19.8	Controller	ICB1 circuit board and wind vane
Springview, NE	1	7/2/99	140.7	Controller	CPU board, matrix boards, output controller board, rotor driver board
	2	7/15/99	384.2	Rotor/ Controller	Blade failure, CPU, and gear box temperature sensor

Figure 5. Blade damage at Searsburg, VT

Retrofits

The surveys conducted by MLI and LTI on the Zond Z-40A, Z-40FS, and Z-50 turbines at the respective sites generally concluded that their lightning protection was not sufficient and numerous recommendations were made for retrofits. The results of the review of the Tacke turbines in Glenmore and the Vestas turbines in Big Spring showed that these turbines had adequate lightning protection.

One of TVP's primary findings was that the Zond turbines had no blade conductors, except for the Z-40A, which has an aluminum push rod in the blade to actuate the ailerons. The Tacke and Vestas turbines both had blade conductors designed for lightning protection. Both of the Zond turbine models without blade conductors have suffered lightning-related blade damage. Zond recently developed and tested a retrofit for the Z-50 blades, and installed conductors in Algona and Springview this spring. Shown in Figure 6, Zond's "LightningGuard I" conductor retrofit consists of a copper tube that is fed through the interior of the blade, held in place with expanded foam blocks and connected to surface-mounted air terminals at the blade tip.

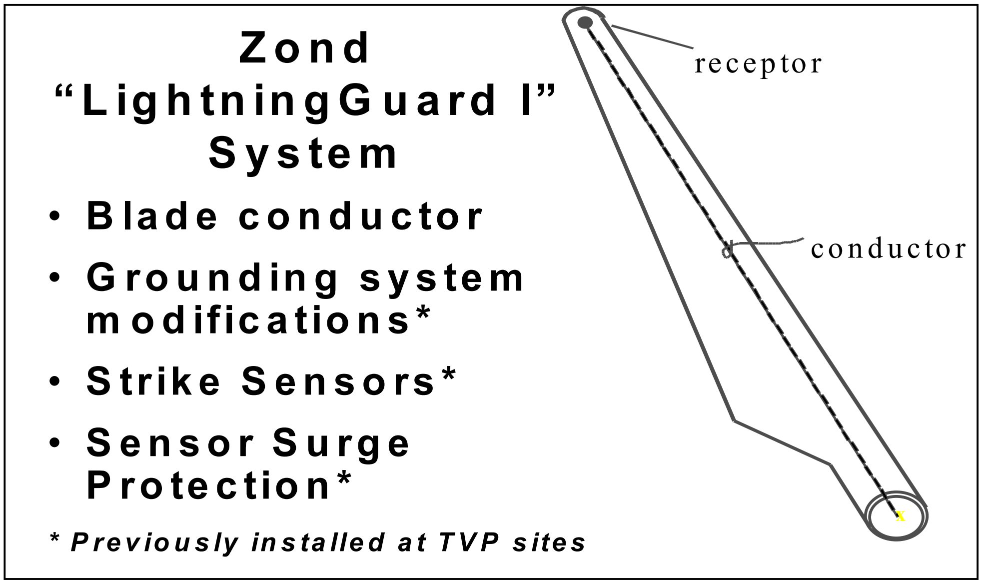

Figure 6. Z-50 "LightningGuard I" retrofit

A variety of other retrofits were identified and implemented on the TVP turbines. These included improvements to the turbine grounding and the controller cable shielding. Figures 7 and 8 show additional modifications made to the Z-50s in Algona and Springview and to the Z-40A turbines in Ft. Davis. The recommended modifications to the Z-40FS turbines in Vermont are similar to those shown for the Z-50. These retrofits typically involve improving the grounding path through the turbine structure, shielding the sensor cables, and improving the earth ground at the foundation. On the Z-40FS and Z-50 turbines, the controller cable shielding was connected at the entry point of the controller enclosures and copper over-braid shield was provided in critical locations such as the anemometer cable.

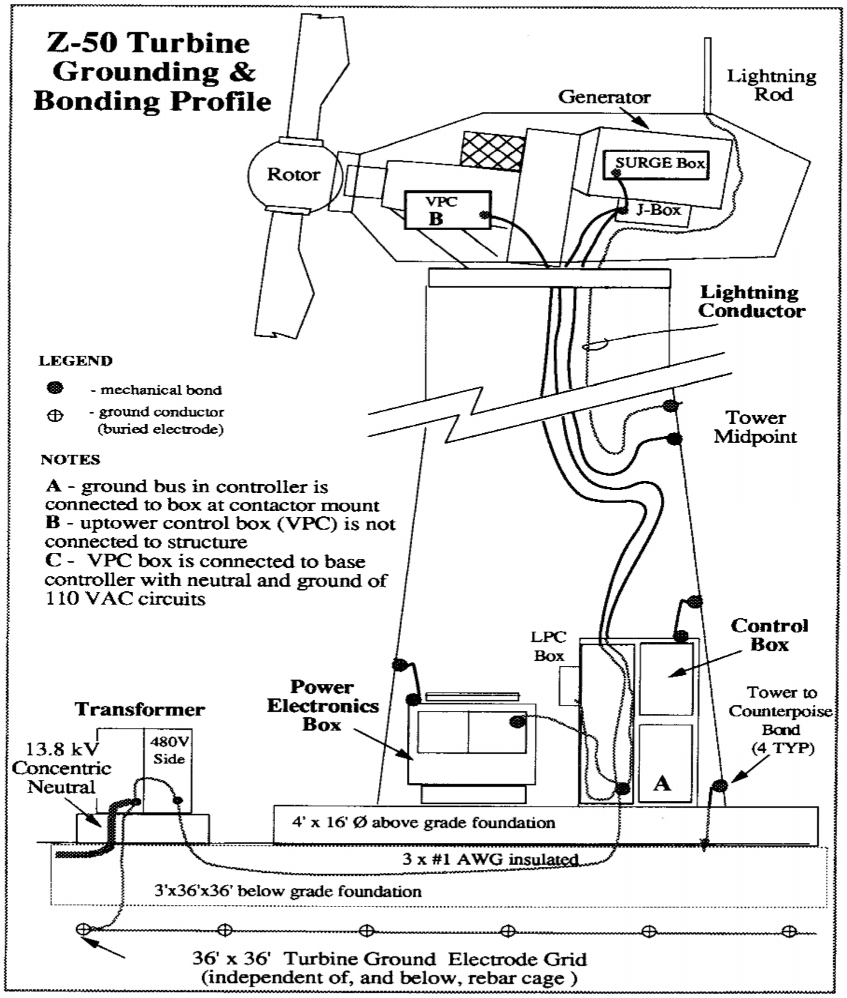

Figure 7. Lightning protection for Z-50s in Algona, Iowa and Springview, Nebraska

Figure 9 shows the earth-grounding arrangement in Big Spring. Vestas' lightning protection is a continuous grounding system, extending from internal blade conductors through the concrete foundations. Based on the experience of local electricians, Big Spring's project owner, York Research, installed lightning arrestors at each turbine transformer and in the overhead power lines in response to lightning-related interruption of radio communications during initial project operation.

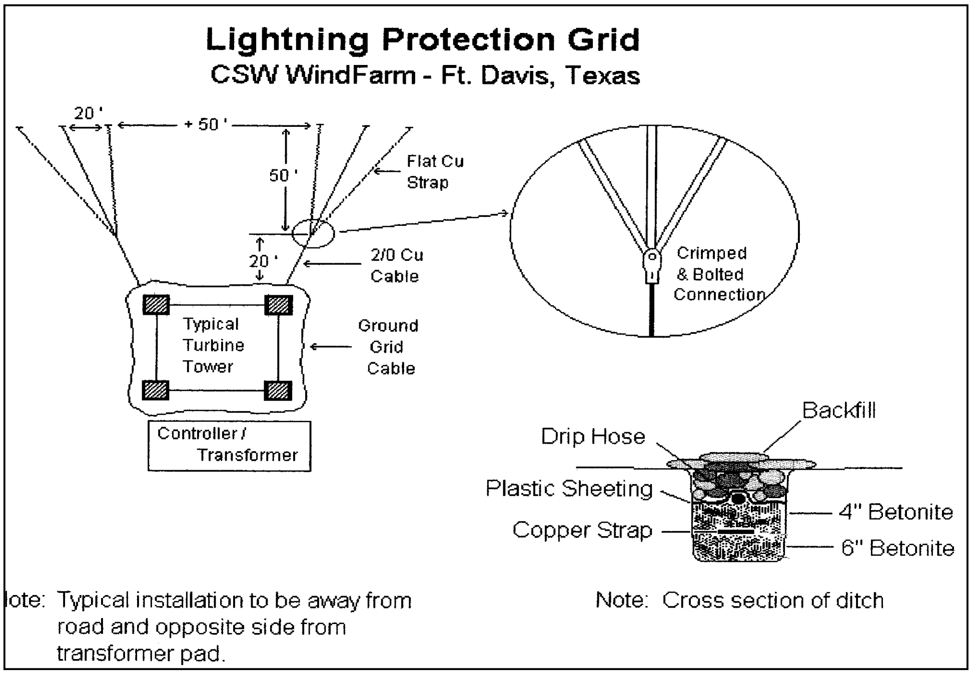

Figure 8. Lightning protection grounding grid in Ft. Davis, Texas

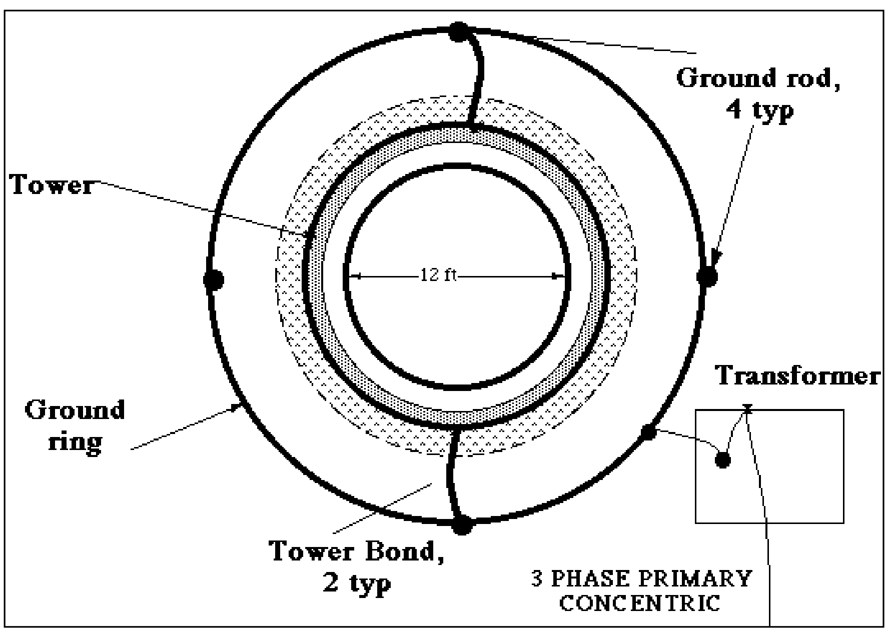

Figure 9. V-47 and V-66 foundation grounding schematic at Big Spring, Texas

Conclusions

At the time when the first TVP project was installed at Ft. Davis, Texas, in 1995, the American wind industry had limited experience with lightning, as most commercial-scale turbines were previously concentrated in windy passes of California where lightning storms are infrequent. Although the TVP is continuing to gain experience and collect information on this topic, some general conclusions and guidelines can be summarized as follows:

- Know your site—assess risk using the National Lightning Detection Network
- Utilize local utility expertise
- Good earth and turbine grounding is important (use plenty of conductor)
- Insist on good protection from turbine vendor
- Blade conductors are essential
- Good bonding and shielding of all control cabling is important, use fiber optic for communication (including up-tower)and SCADA lines in high lightning risk areas
- Strike sensors are useful to rule out lightning for warranty claims
- Insurance and spare parts are important: identify critical and susceptible components such as controller hardware
- Personnel safety is of utmost importance and can be enhanced through early warning systems of incoming storms

The TVP has played a vital role in improving lightning protection strategies used by utilities and wind turbine manufacturers, not only in the United States, but also internationally, through involvement in international forums on wind turbine lightning protection.

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