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Characterizing Wind Turbine System Response to Lightning Activity

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CHARACTERIZING WIND TURBINE SYSTEM RESPONSE TO LIGHTNING ACTIVITY

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ABSTRACT

A lightning protection research program was instituted by National Renewable Energy Laboratory to minimize lightning damage to wind turbines and to further the understanding of effective damage mitigation techniques. To that end, a test program is under way to observe lightning activity, protection system response, and damage at a wind power plant in the Department of Energy (DOE) and Electric Power Research Institute (EPRI) Turbine Verification Program. We installed Lightning activated surveillance cameras along with a special storm tracking device to observe the activity in the wind plant area. We instrumented the turbines with lightning and ground current detection devices to log direct and indirect strike activity at each unit. We installed a surge monitor on the utility interface to track incoming activity from the transmission lines. Maintenance logs are used to verify damage and determine downtime and repair costs. Actual strikes to turbines were recorded on video and ancillary devices. The test setup and some results are discussed in this paper.

1.0 INTRODUCTION

In the early development of wind turbine generators (WTG) in the United States, wind farms were primarily located in California where lightning activity is the lowest in this country. As such, lightning protection for wind turbines was not a major issue for designers or wind farm operators. However, wind turbines are being built in the Midwest, Southwest, and other regions of the United States where lightning activity is significantly more intense and lightning damage to wind turbines is more common. There is a growing need, therefore, to better understand lightning activity on wind farms and its impact on wind turbine operation. In response to this, the Lightning Protection Project [1] was conceived by the National Renewable Energy Laboratory (NREL) to improve the understanding of lightning-caused damage to wind turbines and how to protect them.

Dodd, McCala and Smith [2] carried out thorough literature search on applicable lightning protection to WTG. This report, commissioned by NASA in 1986, contains many valuable insights on how to protect against lightning damage, and it is recommended to all turbine or site designers and operators. However, more recent research in Europe reported on by Cotton and Jenkins [3] and Pedersen [4] shown that the mechanism of lightning damage and its impact on WTG operations are not well understood.

Additionally, protection according to existing standards [5,6,7] and available literature[8] as they apply to WTG still results in significant lightning damage as documented by the University of Manchester Institute of Science and Technology (UMIST) researchers [3] and a Windstats survey.[9]

These surveys indicated that damage due to lightning is the most costly type of downtime event. Even if these events are not as frequent as others, the repair costs and lost revenues can strongly impact WTG operation costs, especially in high lightning risk areas. Without an improvement in the understanding of the mechanisms of failure, the protection systems are somewhat suspect.

In response to these questions, and as part of the Lightning Protection Project, a WTG lightning field test program was devised and implemented in July 1997 at the Central and South West Services (CSW) wind park near Fort Davis, Texas. This field test program was implemented to observe lightning activity, system lightning protection response, and lightning strike damage on a wind power plant in a high lightning risk area. This work was performed in connection with the DOE/EPRI Turbine Verification Program (TVP).

Lightning strikes and attendant turbine damage were detected by video and sensors in the test. The results were very encouraging and we will continue the test into 1998. The test set up, results of the test, and future plans are discussed in this paper.

2.0 LIGHTNING PROTECTION FIELD TEST

A test was devised to observe lightning activity in a typical wind farm and evaluate the system response of each WTG and the whole plant. The test goals are as follows:

1. document lightning activity at the CSW wind park on each turbine and in the wind park
2. survey and document the CSW site grounding and lightning protection system
3. correlate data acquisition with site operations and maintenance (O&M) records
4. correlate measured site data to lightning location information data from the National Lightning Detection Network (NLDN)
5. inform TVP stakeholders and the wind industry in general of progress and results.

The test site is the CSW Wind Park near Ft. Davis, Texas. This project consists of 12 Zond Z-40A aileron control, 550-kW wind turbines installed along two ridges running approximately north-south. All of the turbines are mounted atop 40-meter steel truss towers. Two meteorological towers are installed amongst the turbines. A one-story steel operation building is located on a saddle between the two ridges.

2.1 TEST APPROACH

The site lightning activity is being documented by

- passage of lightning current on each turbine tower and into the grounding system
- strike sensing and mapping within 30 miles
- video surveillance of strikes on turbines and within the wind park
- monitoring of surges incoming to the park from the utility main feeder.

It was not our intent to measure exact lightning currents on the turbines. However, we did want to log lightning activity with an accurate time stamp to allow correlation of data to the NLDN database of strokes to ground triangulated and documented on this continent. From the database we expected to determine stroke peak current and other parameters to correlate to the damage at the turbines.

The grounding and lightning detection system was documented by physical inspection and is partially presented here. Some data are presented in the following section.

2.2 TURBINE STRIKE DETECTION

Three sensors were used to detect and track the flow of direct strike lightning current at each turbine. Attached to each sensor is signal conversion circuitry housed in a cast aluminum box. Data are conducted by optical pulses through fiber to a data acquisition system (DAS) on each turbine. Opto-electronic translation circuitry and a Campbell Scientific CR500 datalogger operate autonomously in this steel box mounted to the base webbing on each tower. Figure 1 shows the sensor layout and DAS arrangement.

The DAS is set up to log frequency pulses coming from the sensor translation electronics that are proportional to strike current and current rate of rise. These counters are polled every 15 seconds. If non-zero counts are detected, the value, time, date and logger ID are saved to final storage for later collection. Data were collected once every two weeks by the site operators using a laptop to directly download each turbine DAS. It takes one hour to download data from all turbines in this manner. The datalogger is powered by a 12 VDC, 7 A-hr battery, and the sensors are powered by 9 VDC batteries. Battery life is about one year.

Two different types of sensors are employed. Both were tested in the Lightning Technologies, a high voltage laboratory in Pittsfield, MA, to verify performance in detecting lightning current. The sensors are discussed in sections 2.2.1 through 2.2.3.

2.2.1 INDUCTIVE LOOP VOLTAGE

The first sensor is based on measuring the magnetic flux (ϕ) change caused by the extremely high current (I) rate of rise at the onset of a lightning strike. We sense this by measuring the induced voltage created by the flux change in a 5 in. wide by 10 in. tall, three turn coil clamped to the edge of a tower leg as shown in Figure 1 as sensor 1. The wire loop acts as a transformer (with N loops), picking up the potential difference (V) along a ten in. section of the tower leg. At the time scale of a lightning strike (several microsecond to peak current), the tower leg voltage is governed by the inductance of the conduction path.

Therefore, the induced voltage is proportional to the rate of change of the lightning current:

$$V_{loop} \propto N \frac{d\phi}{dt} \propto \frac{dI}{dt}$$

This voltage pulse is integrated by the sensor electronics, and the approximate magnitude of the integral is passed to the data logger as a variable duration light pulse through an optical fiber. Our measurement should be roughly proportional to peak current since we are integrating the absolute value of the loop voltage, V(t). The rapid current rate of rise starts at a zero value before the event and essentially terminates (the negative rate of rise is several orders of magnitude lower) at the peak current:

$$I_{peak} \propto \int |V(t)| dt \propto \int_{rise} \frac{dI}{dt} dt$$

The output of a square wave generator is gated at the DAS to the duration of the light pulse. The fixed frequency square wave is conducted to the data logger counter channel only as long as the light pulse is high. The magnitude is indicated by the number of counts. The circuitry is quite simplistic, using discrete components with limited linear region and bandwidth. However, our intent was to determine the order of magnitude of the strike current, not exact waveform characteristics.

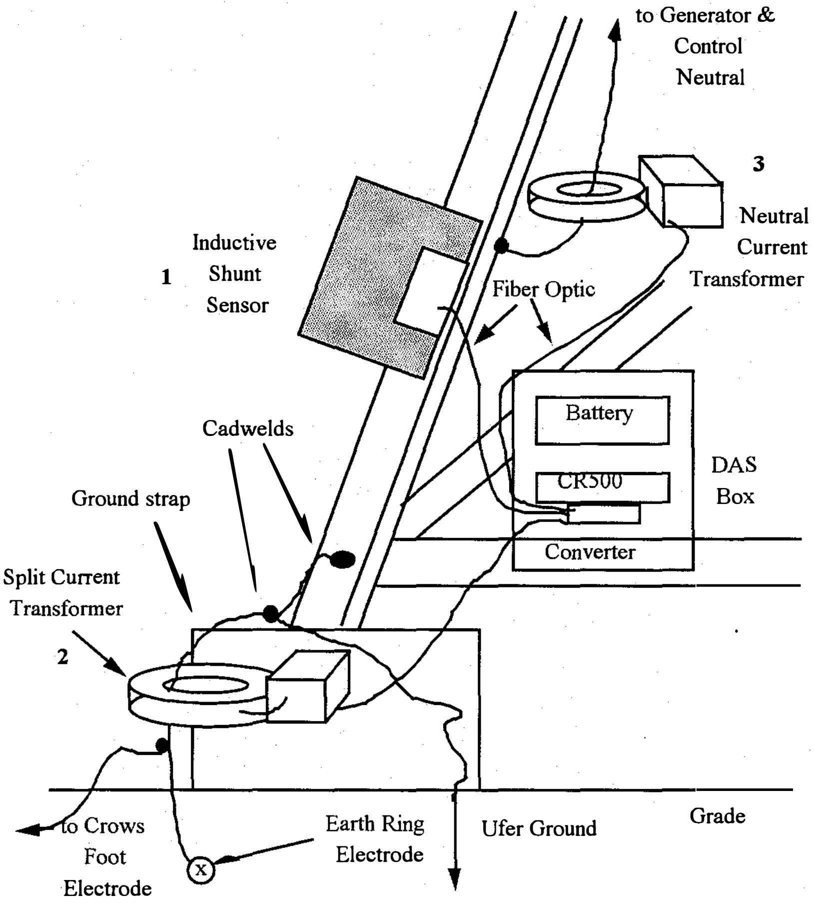


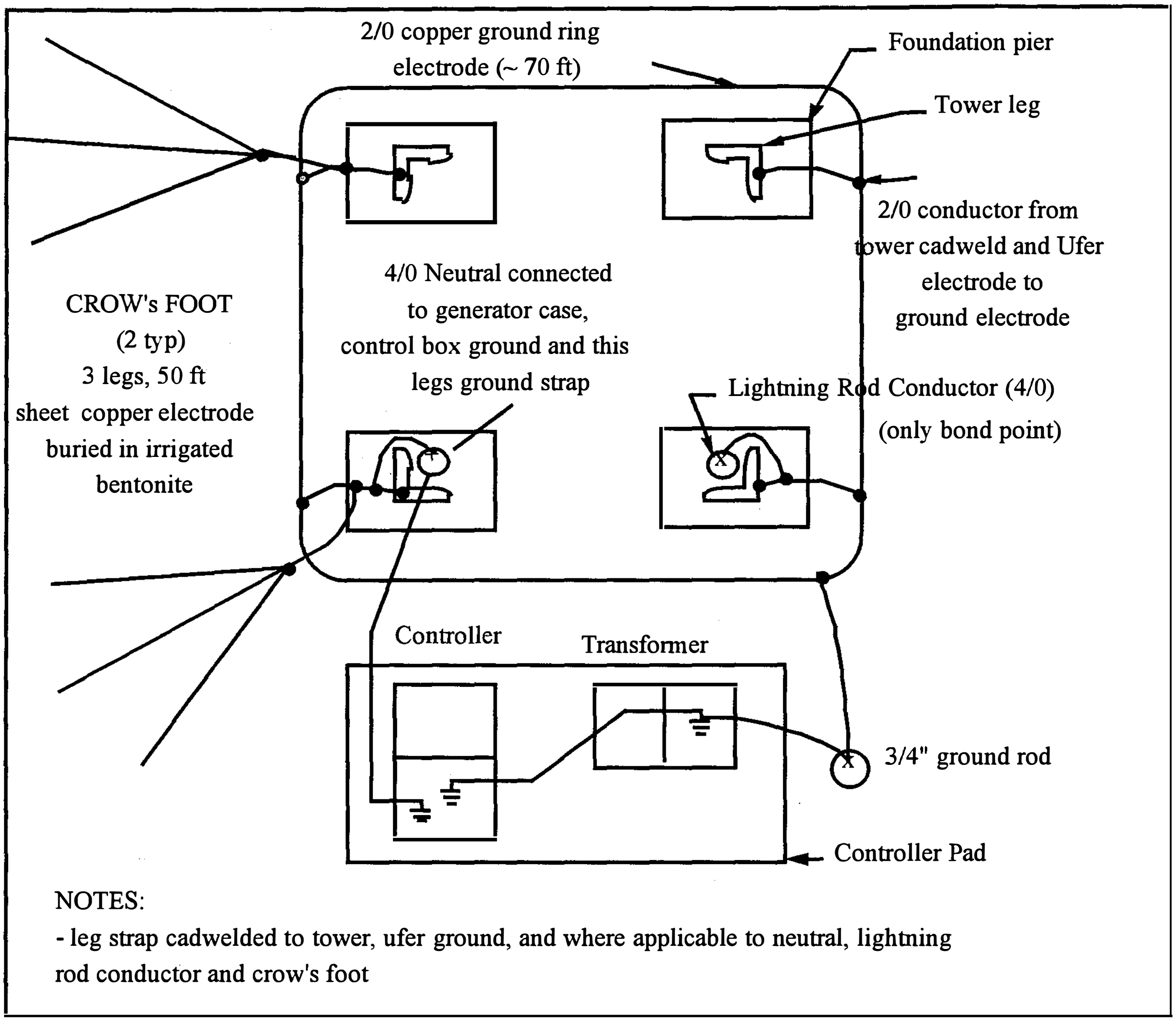
FIGURE 1. LIGHTNING STRIKE SENSORS

2.2.2 GROUND AND NEUTRAL CURRENT

The other two sensors measure the lightning current directly using transformers to step the current down to easily measured levels. The sensor circuit integrates the absolute value of the measured current and again issues a light pulse of proportional duration. The electric charge which is the integral of current can be written as:

$$Q_{charge} = \int i(t)dt.$$

This sensor should be a rough indicator of how much charge passed through the aperture of the current transformer (CT) during the strike. Here again our accuracy is quite limited, not only by the parasitic elements in the circuit, but also by leakage inductance and possible magnetic saturation of the current transformers (primary transformer and PC board mounted CT).



NOTES:
- leg strap cadwelded to tower, ufer ground, and where applicable to neutral, lightning rod conductor and crow's foot

FIGURE 2. GROUNDING PLAN VIEW

On each turbine there are two current sensors: one split torroidal CT is installed around a tower ground strap, and the other is around the generator and controller neutral path to ground (sensors 2 and 3 in Figure 1). The current path sensed by the latter (our so-called "neutral current sensor") is actually the path from the controller box and the generator junction box (attached mechanically to the generator housing) to the ground electrode.

The tower grounds are rather complex (see Figures 2 and 3):

1. each of the four tower legs are tied to a ground wire inside the concrete pier (Ufer ground)
2. each tower leg is connected by copper braid to a ring electrode (100 ft of 2/0)
3. two of the tower legs are connected by braid to 150 ft. of 1.5 in. copper strap buried in irrigated bentonite laid out in 3x50 ft radial crows feet
4. all three phases of the 25-kV buried site feeder have a neutral braid terminated at each turbine transformer box (primary side)

5. the air terminal (lightning rod) on the nacelle has insulated 4/0 Cu welding cable conducting to the ground braid (no bond to tower)
6. the generator J-Box (generator ground) is connected by insulated 4/0 Cu conductor to a tower bond 5 ft. from base (below sensor) and control box
7. the controller path to ground is either via the neutral cable or via the feeder transformer box into a ground rod and the ring electrode; and
8. the controller and up tower generator surge protection device clamps to ground via the neutral path.

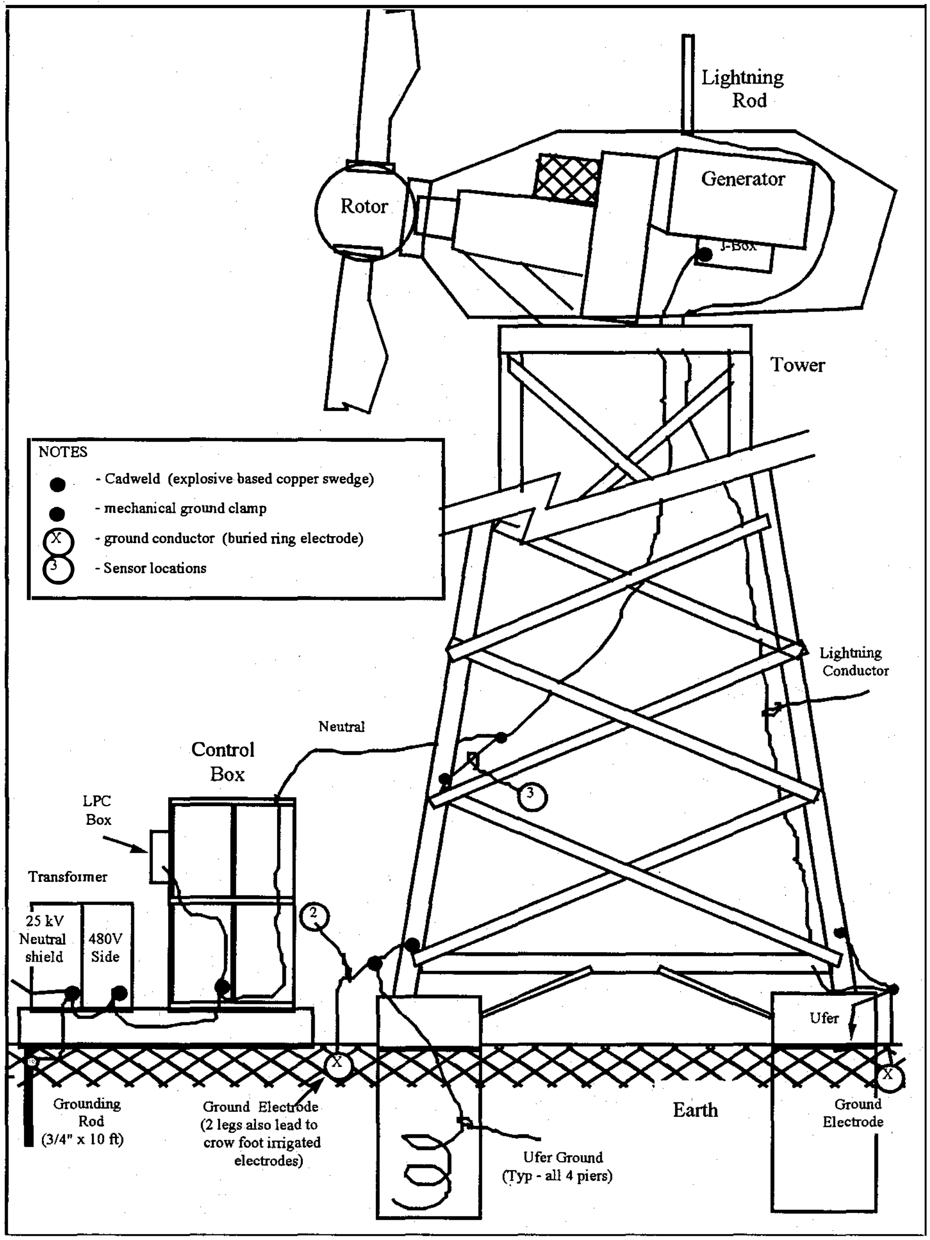


FIGURE 3. TURBINE GROUNDING PROFILE

So, the split CT measures the current into the ring electrode and a crow's foot from one tower leg. It does not include any current in the Ufer ground which is generally accepted to be a good ground, but not as good a lightning ground as a buried ring electrode properly sized for the soil.

2.2.3 SENSOR VERIFICATION AND CALIBRATION

Both types of sensors (and the whole DAS) were tested for accuracy and robustness in the Lightning Technologies High Voltage Lab in June 1997. The calibrations for the sensors were determined there, and they are listed in Table 1.

TABLE 1. SENSOR CALIBRATIONS

Sensor	Min	Cts	Max	Cts	Notes
Voltage Loop	600 A	1	5000 A	120	1 ms rise, 10ms fall
Ground Current	300 A@ 7 ms	1	10 kA@ 7ms	150	Avg peak is higher
Neutral Current	300 A@ 7 ms	1	-	-	NA

Please note that these are inexact by their nature. Our intent is to discern actual strikes from indirect effects, stray motor currents, and ambient noise. We feel quite confident that we have achieved that with the voltage loop. Note, also, that the voltage loop and the ground current sensors can respond to a range of signals. The neutral current sensor, alternatively, merely detects passage of something exceeding the threshold current. It should be stated that we assume that our monitoring locations conduct only 15% (ground current) to 25% (voltage loop) of the direct lightning strike current. This is based on simple circuit assumptions of the tower and grounds (e.g.; four tower legs share equally in the total strike current).

Although lightning strike currents vary significantly, they do have a statistically observed range (see NFPA 780[5]). We sized our electronics to respond to a minimum strike of 5 kA with a rate of rise of 2 kA/ms. More than 97% of all lightning strikes exceed this level. We felt that our low set point is above the average streamer currents and our high set point is in the range of a reasonably sized stroke current. Multiple strokes in any strike (it averages about 3) would, of course, show up as more than 150 counts in the sampling period of the datalogger, as long as they exceeded the minimum sense threshold.

2.3 NEARBY STRIKE SENSING

An Electrical Storm Identification Device [10] (ESID) was installed on the roof of the operation building. This device provides tracking of incoming and developing lightning storms within 30 miles. The roof-top-mounted sensor communicates to a receiving unit in the operations building via fiber optic. The receiving unit is configured to switch relays to activate the video equipment.

We programmed it to provide a time stamped log (serial ASCII stream to the PC) of lightning event counts in four different ranges: overhead (0 to 5 miles), nearby (5 to 10 miles), distant (10 to 30 miles) and cloud to cloud (up to 50 miles distant). We configured the ESID to turn on power to the video cameras when any lightning was detected at all within any 5-minute period. However, video recording and the scanning were activated when nearby and overhead strikes were sensed. If nothing is sensed in these ranges in 5 minutes they were shut off. Finally, the data stream from the ESID to the DAS computer (every 60 seconds) was switched on only when overhead, nearby, or distant lightning was detected.

A PC-mounted hardware/software system called StormTracker [11] was also provided for CSW site personnel to use to track electrical storms up to 300 miles away. This device uses an antenna to directionally locate strikes and plot them on a radar type polar (ring) screen with a custom digital map of the local area superimposed. This has proved to be very useful to the site operators in deciding whether to remain on site for repair or maintenance activity or to delay activity until after a storm passes.

2.4 VIDEO SURVEILLANCE

Two cameras were mounted atop the operations building to record a view of the turbines during electrical storms. Two 1/2 in. CCD cameras equipped with 8-48 mm zoom lenses are mounted in shielded, aspirated enclosures, and the video are recorded using five head commercial surveillance VCRs that provide accurate time stamping and alarm activated recording.

Camera 1 is used to view units 1 through 5 with the 8X zoom lens mounted on a fixed 10 in. stanchion. Zoom, tilt angle, and yaw orientation are manually adjusted. Camera 2 is mounted on an automatic scanner (yaw direction) to repeatedly pan units 6 through 12. Zoom, tilt angle, and yaw limits are manually set. A full-scan cycle of the turbines takes about 15 seconds. Although the dwell time on turbines 6, 7 and 8 are not high, we felt that this was the best solution at the time.

The video system inside the operations building is wired to allow automatic or manual operation of cameras and scanner. As noted above, the VCRs are commanded by the ESID and a relay control distribution box (wall mounted). The two VCRs can be used to review tapes via an A/B switch on a single monitor. The same method can be used to view live feed. We modified wiring in the camera and scanner control to assure that the video system would come on when the automated system commanded it to, no matter what state the operators left it in. To assist operator service, we included warning lamps for tape end alerts and manual over-rides.

2.5 UTILITY LINE SURGES

A power quality monitor (BMI 8010 PQNode[12]) is mounted on the utility side of the site 25-kV distribution. It is used to sample and save current and voltage waveform data when a transient pulse is detected on the 25-kV line. This information is to track whether on site damage is due to incoming transients. We intended that a central DAS computer communicate with the PQNode modem to periodically download data.

During the planning stages of this test, we determined that the CTs were incorrectly sized for the BMI device. It appears that they are properly sized for the standard Schlumberger line meter that is installed on the same pole. This meter is polled periodically by the West Texas Utilities central monitoring system and its scalars would have been incorrect if we changed the 25-kV CTs. Instead we stepped the current down further from the existing CTs to give a final ratio of 120:1 at the line monitor input. Unfortunately there is a loss in accuracy due to this step about 3% range estimated by the CT manufacturer. This is sufficiently accurate for the surge analysis.

2.6 TIME COORDINATION AND STAMPING

The twelve dataloggers, two video recorders, the power quality monitor and the DAS computer had to be synchronized in order to maintain a consistent time stamp. This synchronization was to be used to correlate events with strike documentation from the NLDN database and the Zond/ CSW site monitoring system. The prime reference was a time reference card installed in the DAS computer. Monthly accuracy was estimated to be within 0.5 seconds. We had difficulty with this card, and instead used manual updates from the SCADA computer clock (atomic clock referenced).

The Campbell Scientific loggers were tested for clock accuracy and verified to lose 5 seconds per month. Synchronization was performed by adjusting the laptop clock to the reference computer clock before downloading the dataloggers and allowing automatic clock update.

The video recorders had clocks that time stamped the VHS tapes with a claimed accuracy of ± 1 second per month. These clocks were found to be consistent, and manually updated as needed. The BMI PQNode clock was updated at the time of download by the same computer. Finally, the DAS computer clock was used to directly time stamp the ESID data stream.

2.7 TEST EQUIPMENT PROTECTION

The test equipment was protected against damage by direct strikes and indirect effects from lightning. The DAS boxes are fully autonomous with only fiber optic going into them. The cameras and ESID are grounded to the operations building steel sheathing, and all wires to and from them are either fiber optic or housed in flex conduit bonded to the devices and the building at both ends. The building is grounded in two locations to a buried earth electrode loop surrounding the building. The video coax and phone lines are protected with surge clamping devices connected to the building ground. Additionally, the ESID receiver, the video system, and the PC receive backup power, isolation, and surge protection through an uninterruptible power supply (UPS).

2.8 LIGHTNING PROTECTION SYSTEM

A site grounding and lightning protection survey was conducted and documented. The grounding details are described for a typical turbine in Figures 2 and 3. It appears that the utility line and the communication system are the major catchments for damage due to indirect effects (e.g., surges induced by nearby lightning elevating local potential). A complete lightning protection system description is not presented at this time.

3.0 DATA ANALYSIS AND OBSERVATIONS

The test had very good data recovery. We feel quite satisfied with the operation of the ESID, the video system and the detection sensors. Unfortunately, the BMI line monitor did not prove easy to operate. A review of the data follows.

3.1 TURBINE SENSOR DATA

Data from the DAS indicated three direct strikes to the turbines and many extremely close hits. Table 2 shows a portion of the data associated with the detected strikes. The data is displayed in this table along with the time (local time at the site) and date of the event and the applicable turbine number. The counts in each of the data columns can be multiplied by the scalars in Table 1 to indicate the level of activity. Essentially, any non-zero value in the voltage channel is conducted lightning. Also, the neutral current signal is a counter for ground current activity exceeding the indicated threshold (Table 1). The ground signal is a rough indicator of charge going through the ground conductor. The last two can be ambiguous since it was determined that generator and yaw system start-up is registered in these devices.

Interestingly, many other turbines sensed ground current flow at the same period as the struck unit. The signal level of these events indicate that it was more than just one turbine starting-up. The neutral braid on the 25-kV conductors is the only wiring that connects all of the turbine grounds, and it must be the mechanism for these shared events.

There are also many events wherein ground current flow is detected by up to 12 units simultaneously during lightning activity periods, even without strikes to turbines. We suspect that many of these events are from surges incoming on the utility line-especially in the cases where Units 3 through 5 are simultaneously "hit." These are the units closest to the incoming utility feeder. However, some of these are from strikes close to a turbine that raises the local potential and drives a current flow to other turbines via the 25-kV conductor neutral braid. This means that the conductor shares the current of a strike to some other turbine ground systems.

We believe that there is some interesting information to be garnered from evaluating this hit

TABLE 2. DATALOGGER STRIKE SUMMARY

Item	Date	Julian Day	Time (hrmin) *	Time (sec)	Unit No.	Lightning Voltage (cts)	Ground Current (cts)	Neutral Current (cts)
1	**27 July**	**208**	**1631**	**30**	**11**	**108**	**156**	**1**
	27 July	208	1631	30	7	0	148	1
	27 July	208	1631	30	8	0	163	1
	27 July	208	1631	30	10	0	156	1
	27 July	208	1631	15	9	0	159	1
	27 July	208	1631	15	12	0	159	1
2	**27 July**	**208**	**1632**	**0**	**1**	**210**	**223**	**1**
	27 July	**208**	**1632**	**15**	**2**	**9**	**227**	**1**
	27 July	208	1632	0	7	0	142	1
	27 July	208	1632	0	8	0	0	1
	27 July	208	1632	0	9	0	5	1
	27 July	208	1632	0	10	0	80	1
	27 July	208	1632	0	11	0	163	1
	27 July	208	1632	0	12	0	123	1
3	**18 Aug**	**230**	**2008**	**30**	**5**	**8**	**132**	**2**
	18 Aug	230	2008	30	6	0	0	1
	18 Aug	230	2008	30	8	0	0	1
	18 Aug	230	2008	30	7	0	0	1
	18 Aug	230	2008	30	10	0	0	1
	18 Aug	230	2008	30	11	0	0	1
	18 Aug	230	2008	30	1	0	0	1
	18 Aug	230	2008	30	2	0	0	1
	18 Aug	230	2008	30	3	0	16	0
	18 Aug	230	2008	30	4	0	0	1
	18 Aug	230	2008	15	9	0	0	1
	18 Aug	230	2008	15	4	0	4	0

* corrected clock by -2 minutes for #11 and #8

data and matching it to the site monitoring system database. We expect to explore this in the near future, and we are currently developing a database search methodology for this. We expect to include the data from the DAS, the ESID, and the line monitor as well as operations records.

In our initial downloading of the dataloggers (during the test-readiness period), there were a great deal of "nuisance" current events included in the data stream that did not appear to correspond to periods of lightning activity at the site. During these events, current was being detected in the neutral and ground CTs to absurd levels. When we clipped a current probe on these locations we found that it occurred when the turbines were coming on and off line in marginal winds or when the yaw drives came on. Up to 4 amps at 60 Hz was observed. We can filter out these ambiguities in data processing. In the future, however, the sensor electronics will be modified to stop these events from being registered.

3.2 VIDEO SYSTEM DATA

We recorded unit 1 being struck by lightning on our video system, and digitized it. One frame is shown in Figure 4. A 10-frame movie of the event is available on a web site currently under development (contact authors for the URL). It shows three strokes during the strike.

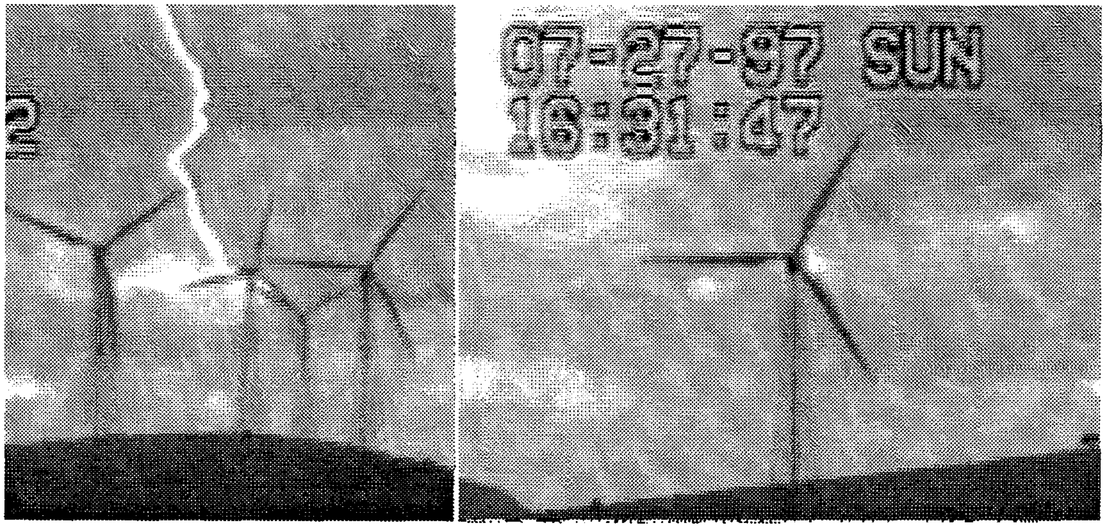


FIGURE 4 LIGHTNING STRIKE TO CSW UNIT 1

The event was located by searching the data logger, and then carefully viewing the corresponding video tape. The strike corresponds to Table 2, item 2. The scanning camera just missed recording the strike to Unit 11 one minute earlier (Table 2, item 1). More than 30 tapes are currently in hand at McNiff Light Industry, but not all have been thoroughly reviewed.

3.3 UTILITY LINE SURGES

Configuring the BMI and downloading the data that we required proved difficult. As a result little useful data was gather from this set up.

3.4 OTHER LIGHTNING ACTIVITY RECORDS

A massive database of all lightning events in the continental United States is maintained by the National Lightning Detection Network (NLDN). We have petitioned Global Atmospherics, the operators of the NLDN, for facilities reports for suspected strikes to units 1 (Table 2, item 2) and unit 10 (no strikes within 15 miles). The report for 27 July focused on unit 1 within ± a half hour of 16:32 CDT. It indicated more than 100 strikes to ground within 5 miles and 8 strikes with probability ellipses overlaying unit 1. The strike shown on the previous page had a peak current of about 20 kA. This report is currently available on the web site.

3.5 PLANT OPERATIONS RECORDS

The strike to Unit 1 damaged the pitch sensor, a pressure transducer, and the main CPU board on the controller. It knocked out the site SCADA system, making it impossible to determine turbine status at the time of the strike. Subsequent inspections indicated that the strike connected at the outboard hinge of the ailerons, conducted down the blade through the pitch push rod, and arced across to the hub surface where the pitch rod enters the hub envelope.

Zond, CSW, and Global Energy Concepts (GEC) maintain data collected from the SCADA monitoring system and the operations and maintenance sheets. The intent was to link to these information sources to compare the status of the turbines and any damage documented to correlate to observed strikes or surges. The SCADA system was down a great deal due to lightning, but the protection for this has been significantly improved during the test. Also, the maintenance and operations records have been matured to provide easily searchable databases. We expect that this information will be more readily accessible during the 1998 lightning season.

4.0 CURRENT STATUS AND FUTURE PLANS

A full lightning season test has been completed. Strikes to two units logged on the sensors and DAS. One of these was captured on video as a blade strike and resulted only in minor controller damage. As a result we feel quite confident in the test system components and setup.

NREL has approved continuing the tests through the 1998 lightning season. As previously indicated, we missed a DAS detected turbine strike with the scanning camera. In the 1998 season we intend to observe all turbines without scanning. To do this, we will fix the camera 2 to view turbines 9 through 12. A third camera with a wide angle lens will be installed to view units 6,7, and 8. Also, supplementing our measurements will be a more mature SCADA and O&M database to assess the impact of lightning activity on turbine operations.

A web page is currently under development to report on the test activities and results to TVP stakeholders and the wind industry. The web page will be expanded further to provide resources for designers and operators and feedback for WTG lightning issues as they arise. Technical papers, such as this, are also being used to share results and information. Also, a database of lightning events (from this and other sites) and the corresponding damage, downtime, and repair costs will be collected to understand the economics of wind turbine lightning protection.

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