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Lightning Protection for the Vertical Axis Wind Turbine

Curtis W. Dodd

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LIGHTNING PROTECTION FOR THE VERTICAL AXIS WIND TURBINE

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ABSTRACT

This report contains the results of lightning protection studies for Vertical Axis Wind Turbines. The methodology is established for determining the chances for a lightning strike at a VAWT site. Proposed designs for lightning protection systems are described. These designs include an insulator design, a brush by-pass design, a cone of protection, lightning elimination device, and a concentric tower protection system. The work also describes an effective grounding system.

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LIGHTNING PROTECTION FOR THE VERTICAL AXIS WIND TURBINE

I. Introduction

A lightning protection system for wind turbines is required to prevent damage from strikes. Injury to blades, bearings, and electrical equipment could occur if adequate protection is not provided. The content of this report shows how lightning protection can be provided for vertical axis wind turbines (VAWTs).

The fact that lightning can do severe damage has been reported by numerous governmental and private agencies. Summaries of these data can be found in The Lightning Book by Viemeister[1] or Understanding Lightning by Uman.[2] Damage to metallic structures such as the turbine can occur due to heating and due to forces produced by the interaction of magnetic fields and high currents.

II. Chance of a Strike

In order to determine if lightning was a threat to the 17-M experimental VAWT at Sandia Laboratories, calculations were made to determine the chance of a lightning strike.[3] It was found that the various techniques for determining this probability gave different results. Details of these calculations can be found in the 17-M VAWT quarterly report.[4]

The technique contained in this report for determining the chances of a strike uses information taken from lightning strike data. Figure 1 shows a straight line relation between the number of strikes and the height of tower type structures. It is only valid for objects up to 200 meters in height. Note that these data were taken in areas where the number of thunderstorm days per year was around 35.

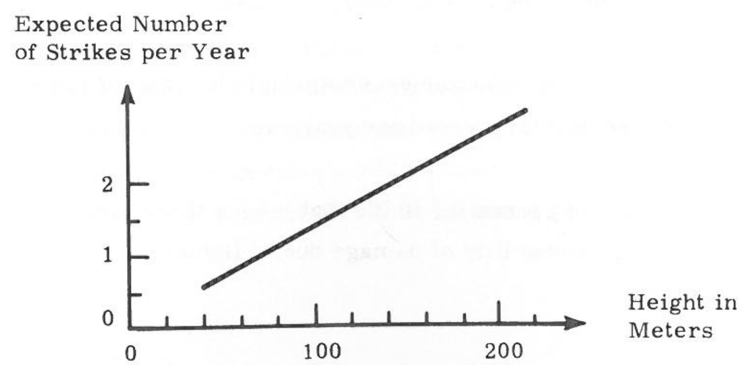

Figure 1. Frequency of Lightning Strikes as a Function of Height in a 35-Thunderstorm Per Year Area (Ref. 6)

The number of lightning strikes per year in a given area is related to the number of thunderstorm days. Although it is not directly proportional,[5] it is close enough that a linear interpolation of the information in Figure 1 gives reasonable results. The example in the next paragraphs illustrate how this information can be used.

In order to determine the chances of a strike to a VAWT, the number of thunderstorm days for that particular location must be known. The United States Weather Bureau has records on the number of thunderstorm days. This information is recorded on the map of Figure 2. For example, a good wind area such as western Kansas has between 40 and 50-thunderstorm days per year.

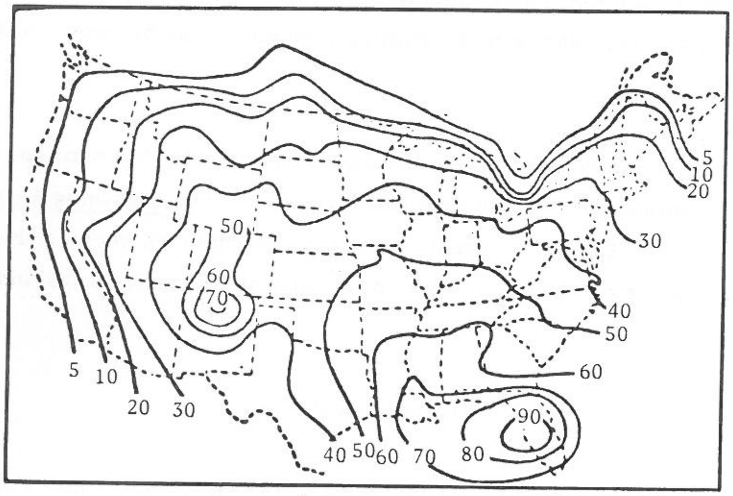

Figure 2. Map Showing the Average Number of Thunderstorm Days Per Year in the United States (Ref. 6)

Consider a 500-kW VAWT located in a location where 45-thunderstorm days per year occur. The height of this size VAWT can be approximated by the relation

$$H = 20 + 2\sqrt{\text{kW rating}} .$$

For a 500-kW VAWT the height would be $20 + 2\sqrt{500} = 64$ meters.

From Figure 1 the number of strikes per year is seen to be .25. If the turbine is in a 45-thunderstorm day region, the number of strikes per year expected is $(45/35) \times .25 = .32$.

If there were 10 turbines in a generating field, that means there would be 3.2 strikes per year to the installation. Clearly, the probability of damage due to lightning increases as the size and number of turbines increases.

It should be noted that, using the height relation $H = 20 + 2\sqrt{\text{kW-rating}}$ and the graph of Figure 1, two 250-kW machines are more likely to get hit than one 500-kW machine.

Using this technique of structure height and thunderstorm days indicates VAWTs will receive lightning strikes. Like all the standard techniques it does not take into account location of nearby structures nor does it consider the terrain of an actual VAWT installation. It does illustrate, like any accepted technique, that wind turbines must have a lightning protection system.

III. Lightning Protection Design

When designing a lightning protection system the characteristics of lightning must be known. Since lightning is a charge transfer process the current characteristics give a sufficient description of a strike. Figure 3 shows the shape of a typical lightning strike. The peak value of current, I_p, is usually 20,000 amperes, but in most lightning protection design procedures, an I_p of 100,000 amperes is considered with a rise time, T_p, of 1 μsec, since it is usually the upper limit of lightning currents. Larger values of current have been recorded, but are very infrequent. A lightning model found in Reference 5 indicates that the 100,000 ampere peak occurs less than 2 percent of the time.

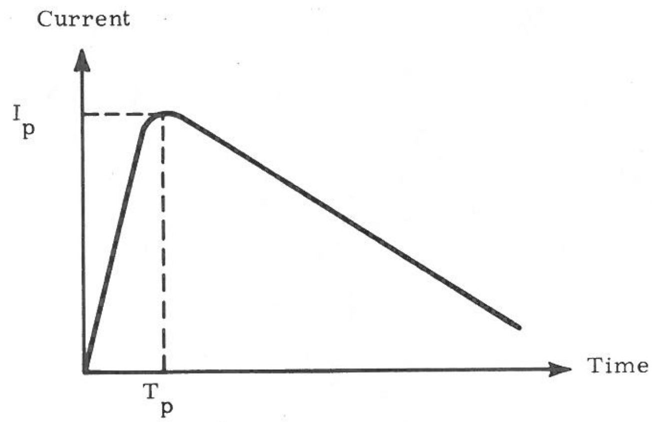

Figure 3. Shape of a Typical Lightning Strike

A sketch of a typical VAWT is shown in Figure 4. Lightning current will flow in the turbine as illustrated in this figure. The currents going down each of the four guy wires should do no damage. If current goes down the turbine shaft, the most probable damage would be to turbine bearings and electrical equipment. It is doubtful if blade damage would occur considering the most likely candidate for blades is an aluminum extrusion. An all aluminum blade would have low resistance and hence the heat production would be low. A direct strike to a blade could cause damage, but this would be unlikely if an air terminal (lightning rod) is of sufficient height above the turbine.

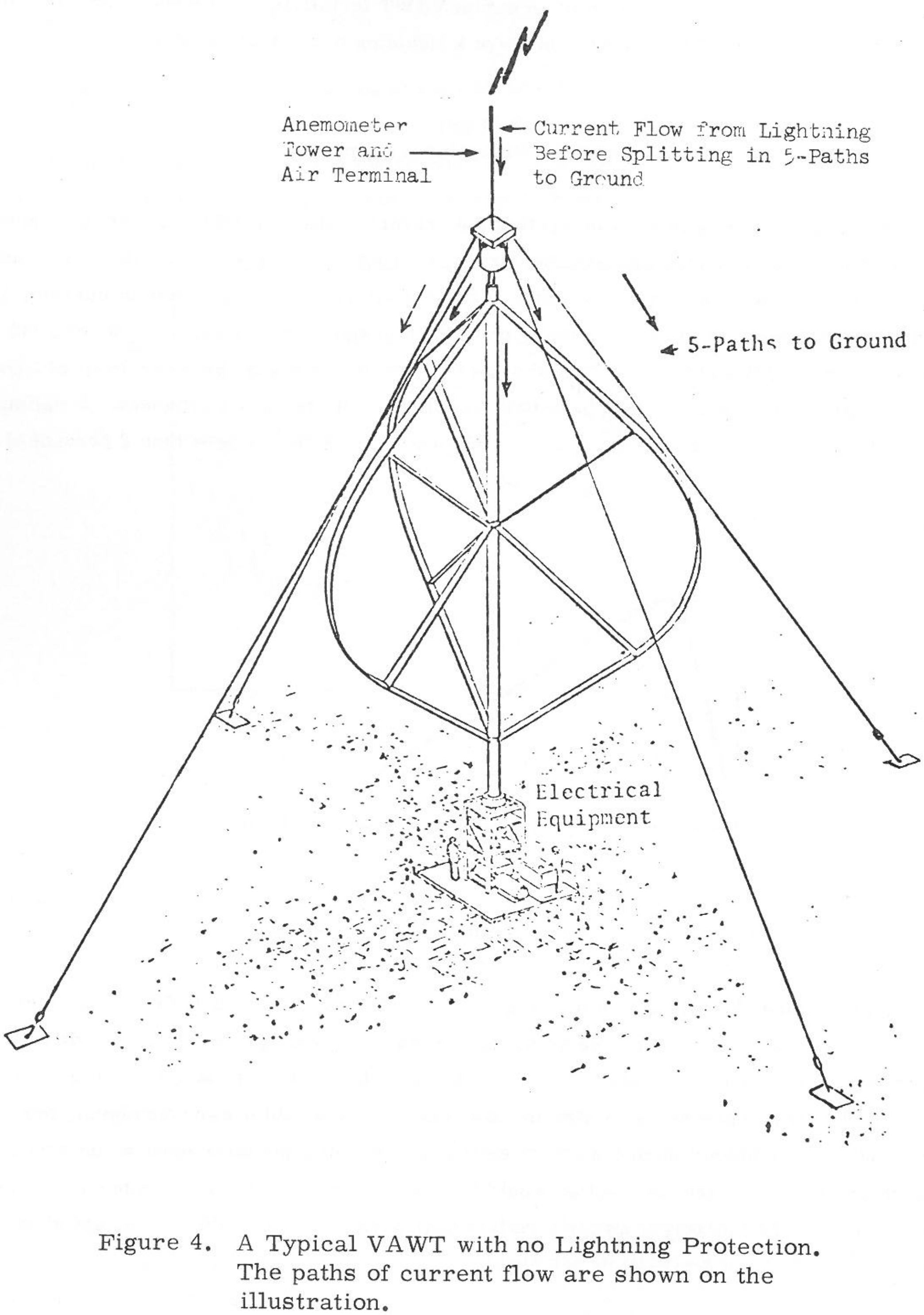

Figure 4. A Typical VAWT with no Lightning Protection. The paths of current flow are shown on the illustration.

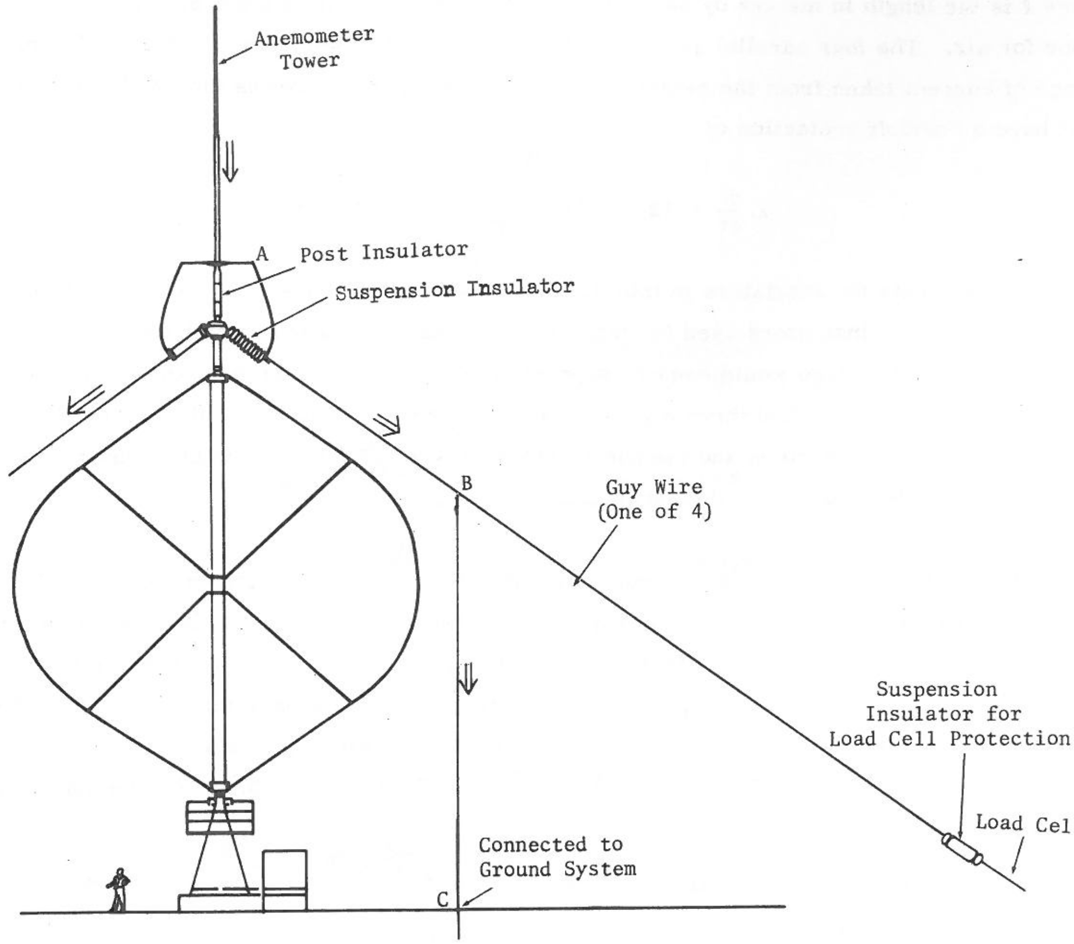

Figure 5. Lightning Protection Using Insulators

Insulator Design

One method to keep lightning currents from going down the turbine shaft would be to place insulators between the guy wires and the turbine shaft and the anemometer tower and shaft as shown in Figure 5. The amount of insulation required can be determined by finding the $L\frac{di}{dt}$ drop on the guy wires.

As an example of how an insulator system would be designed, standard lightning protection calculations for the 17-M VAWT are contained in the next few paragraphs. This method is commonly used in lightning protection design for tall guyed structures. The guy wires have a 0.025 meter diameter and are 40 meters long. If the length is shortened by taking path ABC, 31 meters, the inductance[7] in microhenries becomes

$$L = .2\ell \left(\ln \frac{4\ell}{d} - 1 + \frac{\mu}{4}\right)$$

$$L = .2(31)\left(\ln \frac{4(31)}{.0254} - 1.0 + .25\right) = 48\ \mu H$$

where ℓ is the length in meters by path ABC and d is the diameter in meters. The constant, μ, is one for air. The four parallel guy cables have a combined inductance of 12 μH. The rate of change of current taken from the model is 100,000 A/μsec, which means the insulator material must have a standoff protection of

$$L \frac{di}{dt} = 12 \ \mu H \ 100,000 \ A/\mu sec = 1200 \ KV$$

One candidate for insulators in this design is shown in Figure 5. These are porcelain suspension and post insulators used in transmission lines and power substations. To obtain the necessary standoff voltage would require approximately ten suspension insulators connected in line. Post insulators stacked three high as shown in Figure 5 would probably be suitable for the insulator between the bearings and the anemometer tower. The actual number required would depend on the model number of the manufacturer.

After examination of literature from several porcelain insulator manufacturers, 20 suspension insulators were purchased. These had a tensile strength rating of 50,000 pounds and were the largest size readily available. Tests were conducted and it was found that these insulators exceeded the manufacturer's claims. Cycling in tension between a 15,000 pounds minimum and 25,000 pounds maximum for 10,000 cycles showed no damage to the units. Although tests showed these suspension insulators could exceed the worst case possible for the 17-M turbine, they were not used for the following reasons:

1. For scale up to larger turbines, insulators with proven mechanical strength are not readily available.
2. It was not possible to obtain a sufficient quantity of these suspension insulators in time for them to be put into the 17-M VAWT during construction.
3. No post insulators could be found that would meet the structural requirements imposed by having a 10-meter anemometer tower.
4. Another design appeared feasible and this design would also drain static charge pickup from the blade (this will be discussed in the next section).

It should be pointed out that the above reasons for not using the insulator design should not remove it from future considerations. Some effort has been expended trying to locate materials for insulators which could meet the electrical and mechanical requirements of this design. These preliminary findings are contained in the Appendix. It is recommended that efforts be made to purchase and test some of these insulators. This design, if properly implemented, would give adequate lightning protection.

Brush By-Pass Design

A second method to protect the bearings from lightning damage is to provide a low resistive parallel path to ground. The means chosen for providing a parallel path was carbon brushes shunting critical components. A schematic representation of this design is shown in Figure 6.

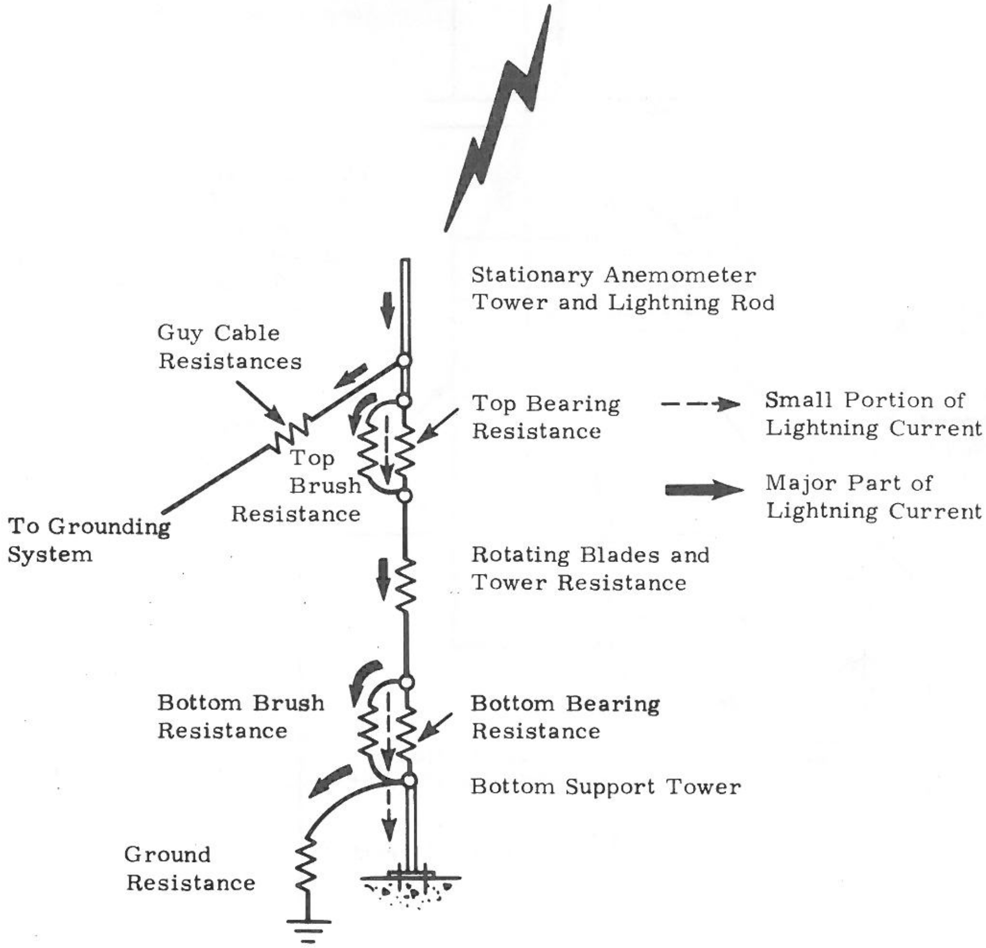

Figure 6. Schematic of Brush Design Showing Current Paths of a Lightning Strike

The design as implemented for the 17-M VAWT can be seen in Figure 7. This type of design has been successfully used for bearing protection on large dish antennas,[8] although the rotational speed of these antennas has been slower than the wind turbines. The validity of this design can be verified to some extent by field tests on the turbines or by testing on a lightning simulator. Because of the time lag and expense of setting up the necessary tests, the brush design was incorporated in the 17-M VAWT with expectations that it will work. Experience gained from using this system on the 17-M VAWT will be of value in determining if it provides sufficient protection. Besides providing a path for lightning current, the brush system also provides a path for static charge developed on the blades.

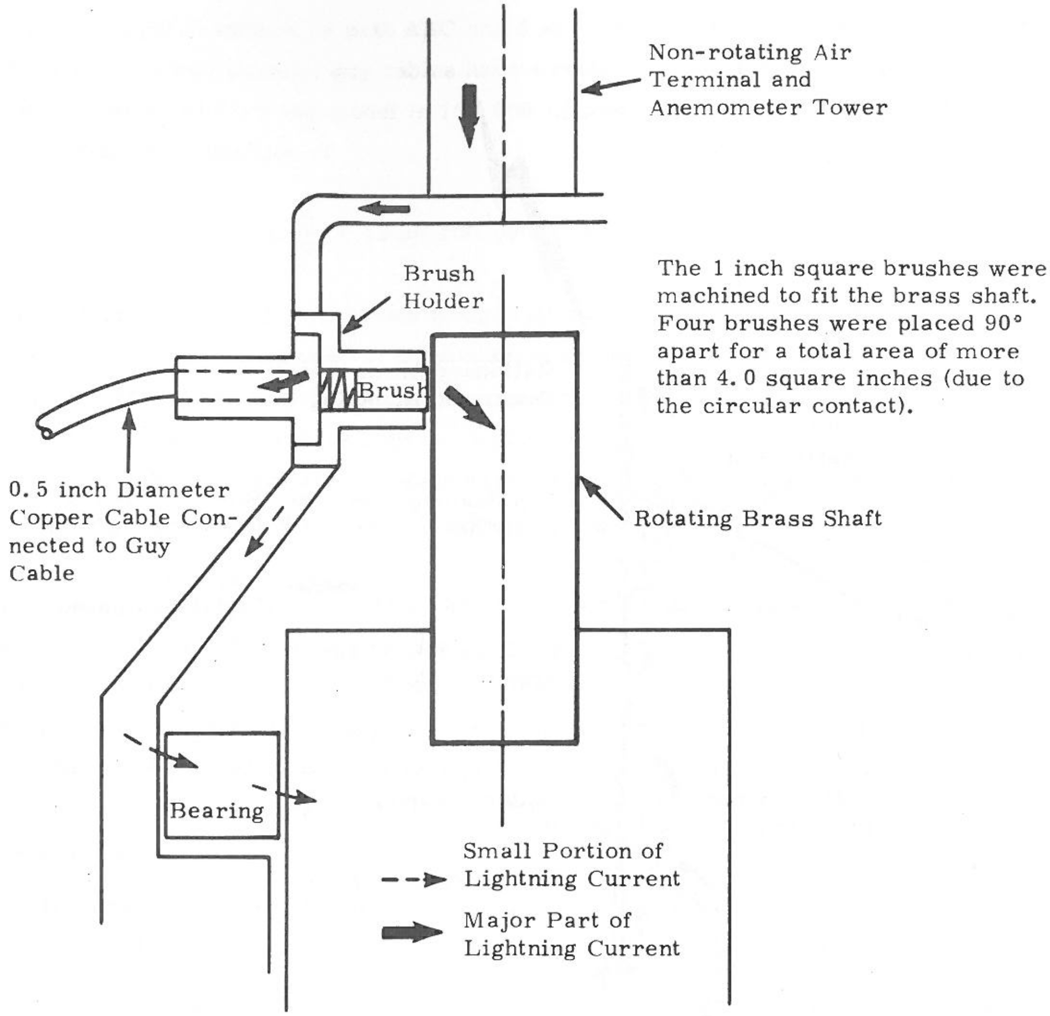

Figure 7. Brush Lightning Protection System as Implemented on the 17-M VAWT. This illustration shows how the brushes were installed at the top of the turbine. It is not an exact copy of the hardware. Brush holders and brushes were installed at the bottom of the turbine to by-pass the lower bearings.

Cone of Protection

The cone of protection method is based on the theory that lightning will strike the tallest object in a given area. If a cone is drawn about a tower as shown in Figure 8, then any object within that cone is considered protected. An angle, θ, of 45° is considered to give adequate protection. The largest angle allowable for protection is subject to some debate.

The reason for not using this technique is based purely on economics. It is estimated that the protective tower must be 50 percent taller than the VAWT tower to provide adequate protection. The cost of this larger tower and the additional construction cost makes it impractical.

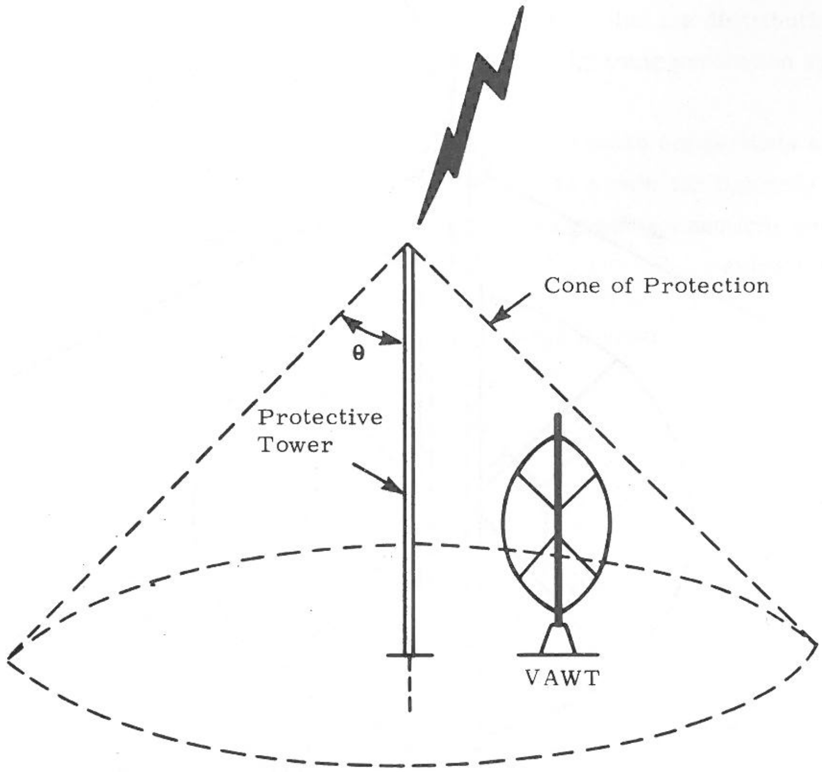

Figure 8. Cone of Protection Method

Lightning Elimination Device

A system which would cause lightning not to strike has been suggested by Carpenter.[9] Although this technique appears to have some acceptance as a useful means of protection, no scientific evidence was found that verified it did indeed work. The results of a study by Bent[10] indicate it failed to function as claimed by its manufacturer.

Concentric Tower Protection

If a VAWT were constructed using the concentric tower design, it would be possible to use the non-rotating center tower as a terminal. Figure 9 illustrates how such a system would work. Because of the low resistive path of the center shaft, very little lightning current would pass through the bearings. However, it may be necessary to have brushes near the bottom on the rotating shaft for static discharge.

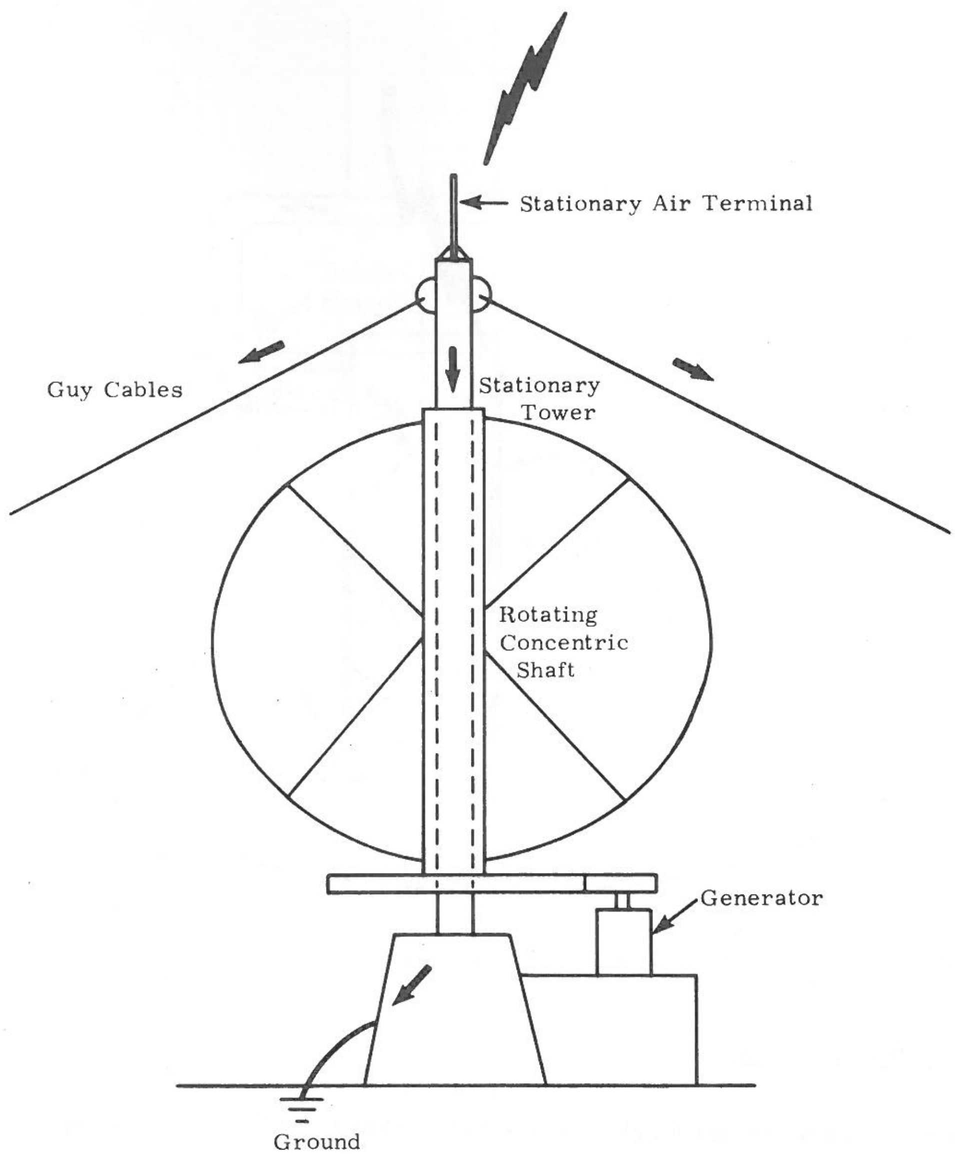

Figure 9. Lightning Protection for a Concentric Tower VAWT

IV. Grounding System

Whether using the insulator system or the brush by-pass system for protection, a good ground must be provided. Marshall[6] is an excellent reference for grounding system design. Methods of providing a good ground depend on the soil conditions in the vicinity of the turbine. The dry, sandy soil located at the 17-M VAWT site has a high resistivity when compared with a high moisture content loamy soil. The grounding system for the 17-M VAWT should be adequate at most wind turbine sites.

At the 17-M site a ground system consisted of 10-ft long ground rods connected together with 0.5-in. diameter copper grounding cable. The ground rods were spaced on approximately 10-ft centers around the turbine pad as shown in Figure 10. Also shown in Figure 10 are the ground rods and cable running radially toward the guy cable anchors. Drop cables from the guy cable ends were connected to these radial runs. All below grade bonds were made with Cadweld* connections. Measurements at the site showed a ground resistance of less than 1.0 ohm. The code on Kirtland Air Force Base requires resistance of less than 5 ohms.[11] This low resistance, plus the distribution of ground currents in the grounding grid, are typical of what is needed in a lightning protection system.[12, 13]

After installation of the grounding grid, it is necessary to make connections to the cables coming down from the turbine tower. This must be done to provide a path for lightning current to ground as can be seen when referring back to Figure 6. These above grade connections were made using cable clamps.

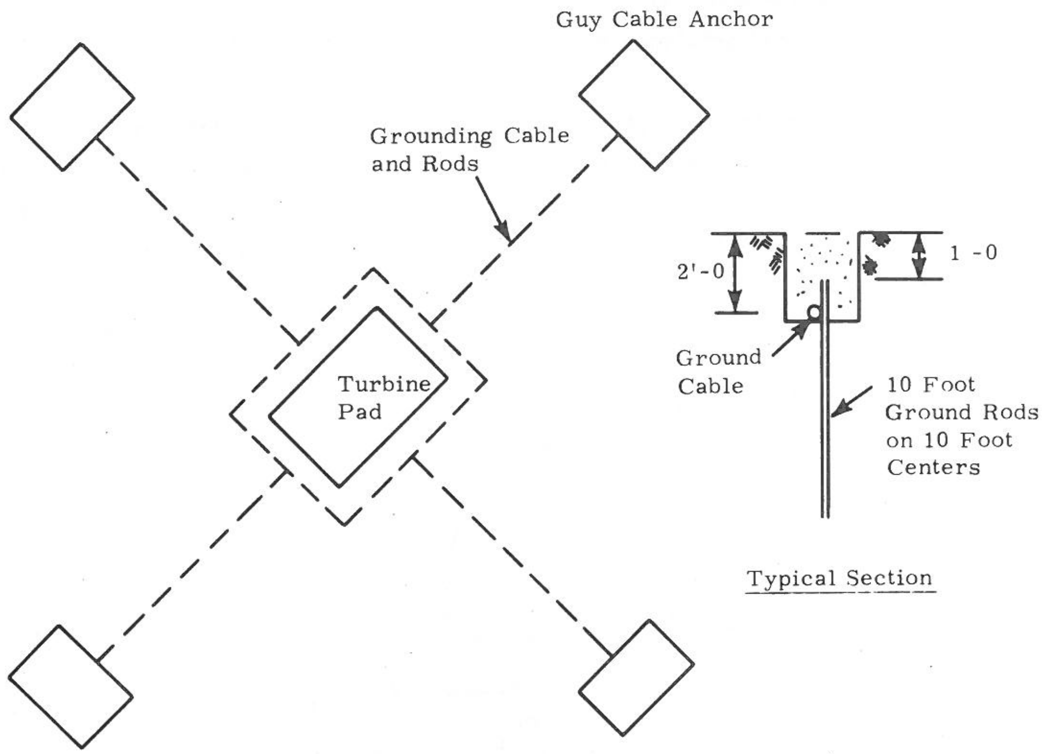

Figure 10. Grounding System for 17-M Turbine

V. Conclusion

Lightning protection is needed for wind turbines as has been indicated by the chances of a strike calculation. Examination of the 17-M VAWT after a thunderstorm on July 20, 1977, indicated a non-damaging strike has occurred to this relatively short experimental machine. Although the brush by-pass system seems to give adequate protection, the insulator design discussed in the report may also give protection at nearly the same cost.

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*Cadweld is a trade name for a mold type welding operation. It is normally used in New Mexico, and perhaps other areas, to make below grade connections in grounding systems.

APPENDIX A

Suspension Insulators

The insulator protection system cannot be implemented unless suspension insulators with suitable mechanical and electrical properties can be obtained. The lightning protection system using insulators is illustrated in Figure 5 of the text. It should be noted that both post type and suspension type insulators are shown in this illustration. Ceramic post insulators meet mechanical and electrical requirements for protection when an air terminal is attached to the top of the turbine. For this reason, only suspension insulators are included in the discussion.

Porcelain suspension insulators are used extensively in electrical power transmission lines. A typical insulator is shown in Figure A-1. To obtain the necessary standoff voltage, these insulators can be connected in a string. For example, if each insulator has a positive impulse flashover of 125 KV, 10 connected in a string will give a protection of 1250 KV. Although there is a limit to how many can be hooked in a string, it is possible to obtain standoff voltage suitable for any size VAWT now under consideration.

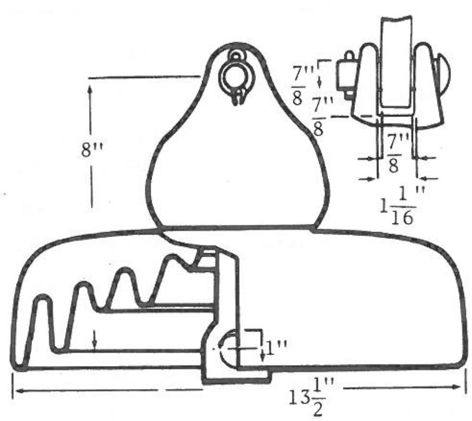

Figure A-1. A Typical Porcelain Suspension Insulator

The main problem associated with the available porcelain insulators is their lack of tensile strength. There is no domestic manufacturer that makes porcelain insulators with a tensile strength greater than 50,000 lb. Although this size would be suitable for lightning protection of the experimental 17-M VAWT, when going to large size turbines, it would be necessary to obtain porcelain suspension insulators with more strength or use strain yoke sets which connect insulators in parallel strings. A disadvantage of taking parallel strings would be the cost, extra weight in the tie-down system, and the additional construction cost. The 50,000-lb tensile strength of porcelain insulators purchased for testing[14] weighed 23.5 lb each and cost $25 each.

To illustrate values for cost and weight, and to examine construction problems consider a 500-KW VAWT. A turbine this size would be approximately 200 ft in height with a tension of 200,000 lb on each guy cable. This means 12 parallel strings of 20 insulators each would be required on each guy cable if a safety factor of 3.0 is used. This means a total of 960 insulators would be needed at a cost of $24,000 and with a weight of 22,500 lb. The handling of 960 insulators of 25 lb each would certainly add to construction cost. This example illustrates that a porcelain insulator is not a strong candidate for a component of the insulator lightning protection design.

The use of materials other than porcelain may make the insulator design still a candidate for lightning protection. There are at least six non-porcelain insulators presently being tested by the Bonneville Power Authority,[15] BPA, which should be considered for the insulator design. The results of these tests should be available and will be published sometime in the future. Table A-I shows the companies, location, and briefly describes each of these insulators.

TABLE A-I

Manufacturers of Non-Porcelain Insulators

Company	Location	Description
Joslyn Reinforced Plastics	Cicero, IL	Fiberglass core with synthetic rubber
The Ohio Brass Co.	Mansfield, OH	Fiberglass core with synthetic rubber
Permali, Inc.	Mt Pleasant, PA	Fiberglass core with cycloaliphatic epoxy weather rings
Rebosio	Italy	Teflon and synthetic rubber
Rosenthal	West Germany	Reinforced synthetic rubber
Sediver	France	Fiberglass and plastic

Detailed pricing and technical information on each of the insulators in the table have not been obtained at this time. Information obtained from Permali, Inc., is given so a comparison can be made with the porcelain insulators. Their plant in England makes a fiberglass core insulator with cycloaliphatic epoxy weather rings. The insulator shown in Figure A-2 has a positive pulse flashover of 1840 KV and a tensile strength of 100,000 lb. This insulator weighs around 200 lb and sells for $1400 each in small quantities. Permali has indicated these insulators could be made with greater tensile strengths. It is possible one such insulator in each tie-down would be sufficient for the insulator design.

Tests by the BPA may show that suitable insulators are available for the insulator lightning protection design. If the price of these insulators is low, the insulator lightning protection design may be an alternative to the brush by-pass design.

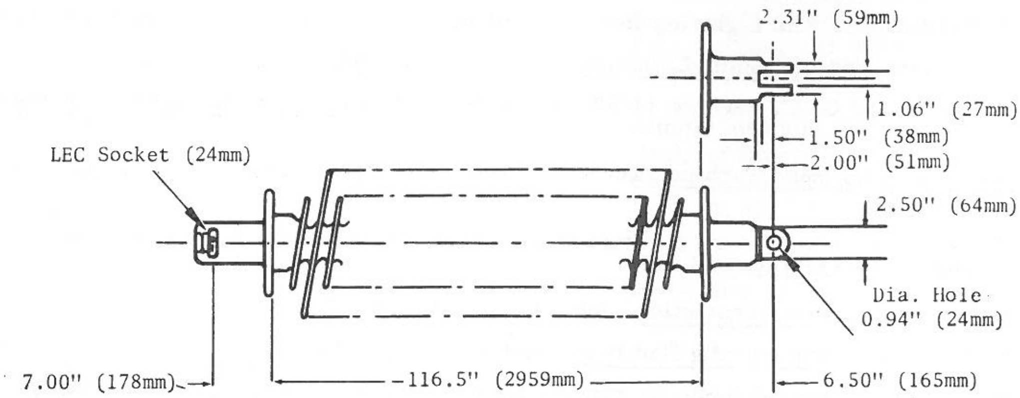

Figure A-2. Suspension Insulator with Fiberglass Core and Cycloaliphatic Epoxy Weather Rings (Permali, Inc.)

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