THE CONVERSION OF WIND ENERGY TO ELECTRICITY

by

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ABSTRACT

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The wind close to ground level contains an inexhaustible supply of energy. This energy is abundant enough to significantly alter the bleak future of our energy supply that some experts predict.

The technology for converting wind energy to electricity exists today. Other related technologies such as energy storage and controlling the electricity are also advanced enough to allow large scale production of the equipment for those tasks. The source of energy, the wind, is free and it is not subject to taxation or foreign control. Also, the ecological impact of extracting energy from the wind is minimal.

Improvements are still needed, however. The cost to generate electricity from the wind is just now becoming competitive with conventional methods. New technology is needed to overcome the inherent weaknesses of wind energy that contribute to this high cost: its unsteady supply and relatively low energy density. Equipment, installation, operation, and maintenance costs must be analysed further,

also.

This thesis will examine thes points and briefly discuss the preliminary design for one particular windmill installation.

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LIST OF SYMBOLS

SYMBOL	DEFINITION	UNITS OR REFERENCE
a	Interference factor	none
A	Area	m^2
A_f	Platform area of an airfoil	m^2
A_p	Frontal area of an airfoil	m^2
B	Magnetic induction	T
C_D	Drag coefficient	none
C_{Df}	Frictional drag coefficient corrected to frontal area	none
C_{D_p}	Pressure drag coefficient	none
C_f	Frictional drag coefficient	none
C_L	Lift coefficient	none
C_p	Power coefficient	none
d	Diameter	m
D	Drag force	N
D_f	Frictional drag	N
D_p	Pressure drag	N
E	Energy	J
E	Voltage	V
E_K	Kinetic energy	J
f_e	Excitation frequency	s^{-1}
f_r	Rotational frequency	s^{-1}
F	Force	N
F_c	Centrifugal force	N
F_Q	Torquing force	N
H	Height above ground	m

i	Current	A
I_m	Mass moment of inertia	$k_g \cdot m^2$
k	Coefficient of fluctuation	none
k	Drag over lift coefficient	none
k	Ratio of specific heats	none
l	Length	m
L	Inductance	H
L	Lift force	N
m	Mass	k_g
$\dot{m}$	Mass flow rate	k_g/s
n	Number of turns per unit length	m^{-1}
P	Pressure	Pa
P	Power	W
P_0	Output power	W
Q	Volume flow rate	m^3/s
r	Radius	m
R	Radius	m
R	Resistance	Ω
R	Resultant force	N
S	Surface area	m^2
T	Time	s
T	Thrust	N
v	Wind velocity	m/s
v_r	Relative velocity	m/s
V	Velocity	m/s
V	Voltage	V
w	Density of energy	J/m^3

W	Magnetic energy	J
α	Angle of attack	$^\circ$
β	Angle	$^\circ$
δ	Angle	$^\circ$
ζ	Decreasing factor or reduction coefficient	none
η	Efficiency	none
Θ	Pitch angle	$^\circ$
μ	Tip speed ratio	none
μ_0	Permeability constant	H/m
ρ	Density of air	k_g/m^3
σ	Normal stress	Pa
τ	Shear stress	Pa
ϕ	Angle between v_r and plane of rotation	$^\circ$
ψ	Angle	$^\circ$
ω	Angular velocity	s^{-1}

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The purpose of this study is to investigate the feasibility of using wind powered machines to generate electricity. After the various aspects of wind power are understood, a small windmill installation, suitable for supplying electricity to a family dwelling, will be discussed.

The demand for energy is beginning to surpass man's ability to produce it via conventional means. In addition, our supplies of energy fuel are becoming increasingly difficult and expensive to recover. There is a distinct possibility of exhausting some of our sources of fuel within the next few decades.

Because of this situation, unconventional sources of energy are receiving a great deal of attention. Wind power is one of the foremost sources of energy that is being studied. The United States government, colleges and universities, private research companies, foreign governments and institutions, scientific organizations and societies, and interested amateur researchers are all turning their sights to the wind as a source of energy. Various predictions estimate that anywhere from 1 to 10% of the electricity generated in the United States in the future will come from the wind.[1]

Background

The energy in the wind is free to be harnessed by man for his purposes. The technology for doing this had its beginning thousands of years ago. The earliest known windmills appeared in Persia about 644 A.D. Prior to that, wind was used to propel sailing ships, river boats and other water craft. Denmark had the most successful program for generating electricity by wind power in the early twentieth century. Windmills in rural America were used mostly for pumping water, grinding grain and powering sawmills, though some were converted to generating electricity. A great deal of windmill development and improvement has taken place during the twentieth century in Denmark, England, France, Germany, Russia and the United States.[2]

The largest windmill ever built was the Smith-Putnam Wind-Turbine at Grandpa's Knob near Rutland, Vermont during World War II. It had a 53 meter diameter blade and was rated at 1250 kilowatts. The S. Morgan Smith Company of York,

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[1]Theodore W. Black, "Something in the Wind? ERDA Thinks So," <u>Machine Design</u>, Vol. 48, No. 12, (May 20, 1976), 18.

[2]Deane McCarthy and George Rosen, "Statement of Deane McCarthy and George Rosen," <u>Hearing before the Subcommittee on Energy of the Committee on Science and Astronautics</u>, U. S. House of Representatives, No. 49, (Washington: U.S. Government Printing Office, 1974), pp. 209-210.

Pennsylvania backed this project in hopes of developing a new product, and Palmer C. Putnam designed the windmill and directed the project. The windmill successfully supplied electricity to the Central Vermont Public Service Corporation off and on from October 1941 to March 1945. Due to the war effort, materials were difficult to secure and at one point the windmill sat idle for 25 months waiting for a replacement for a failed bearing. The project came to an end the morning of March 26, 1945 when one of the 7300 kilogram, stainless steel blades broke at its root and was tossed 230 meters. At this time the S. Morgan Smith Company reviewed the entire project and decided to abandon it. While the project was a success technically, and a great amount was learned and recorded, it was much less of an economic success. The electricity generated was not competitive with conventionally generated electricity. Several ideas for bringing the cost in line were suggested, but these would have required several hundred thousand dollars to test and evaluate. Since the S. Morgan Smith Co. had already spent much more than they had initially estimated; over a million and a quarter dollars total expense; they decided to end the project since no reasonable guarantee of economic success could be made.[3]

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[3] Palmer Cosslett Putnam, Power from the Wind, (New York: Van Nostrand Reinhold Co., 1948), pp. 10-14.

Research into windmills, as well as into the related topics of energy storage and methods of controlling the output, has accelerated in the 1970's. In fact, all possible sources of energy are receiving attention: wind, solar, geothermal, and the movement of the tides and ocean currents to name a few. This is spurned by the increasing cost of fossil fuels and by the realization that these reserves are not infinite.

Steps to Determine a Windmill Installation

Three factors are involved in establishing a windmill installation. The first stage is to decide the broad design features. This has nothing to do with the aerodynamic design or the stresses in the components. It is basically a determination of the form of the output. Some questions which need answered here are: Is the windmill required to supply AC electricity, DC electricity, pump water, or do other tasks? How much energy is needed? Will other sources of energy supplement the windmill or will the windmill have to supply everything? Is energy storage going to be used?

The second stage to developing a windmill is to select the installation site. The third stage is the detailed design of the windmill itself. The first two stages are determined by each individual case. While the detailed design of a windmill blade can be done on a drawing board and in a lab anywhere, the broad design and the site selection can only be done by the people on the spot who are developing that particular installation.[4]

Broad Design

The first stage, or determining the broad design features, must settle the type and amount of energy to be supplied. Direct current electricity greatly simplifies the controls which helps reduce the initial cost. Alternating current on the other hand, requires some form of control to deliver the desired frequency. DC in low voltages has the disadvantage of excessive power loss if it is transported over long distances. The greater cable size to transport DC will quickly diminish the other savings associated with it. If the electricity is to serve a home or other established user, AC is more compatible with existing appliances and wiring. If the electricity is needed for a job such as supplying energy for light and communication at a wilderness scientific station or an offshore oil production platform, then DC may prove to be the better type. The amount of electricity to be generated can be determined by the anticipated demand and will probably be expressed in kilowatt-hours or in amperes. If AC is desired, the frequency must be specified. In some cases the voltage will have to be pinpointed and in other cases it will not. For example, if the electricity is

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[4]L. Sterne, "The Need for Simplicity in the Design of Windmills," International Seminar on Solar and Aeolian Energy, Sounion, Greece, Sept. 4-19, 1961, (New York: Plenum Press, 1964), p. 159.

to serve a house, the voltage will have to be 115 volts. If the electricity will be used where the electrical devices must be specially designed, then the voltage can be determined as a part of the detailed design of the entire project in order to allow the greatest possible overall economy.

If water is to be pumped, a choice lies between pumping water directly, and generating electricity to run a pump. The same choice applies to providing power to run a heat pump. Another possible use of wind energy is to convert the energy to heat. Finally, a need still exists for wind power to supply energy to a grinding mill, sawmill, or other machines, especially in developing regions.

Another element of the broad design stage is to decide what other sources of energy, if any, will be used. The windmill can be supplemented by a diesel powered generator, by purchased electricity from a utility company, or by solar energy. Presumably, diesel or the utility company will always be available when the windmill cannot supply power. Solar power may not be that reliable. This should be noted during this stage.

Out of all these possibilities, two prevalent approaches for a windmill installation are being proposed. One of these is to feed generated electricity into an existing power grid system. This will require many medium to large sized windmills located in wind prone areas. The expense of energy storage is eliminated. The wind generated electricity will reduce the fuel consumption of the utility. As the cost of fossil fuels increases the economics of this system become more favorable.

The other approach is to develop an independent, or base load, supply. This is generally proposed in conjunction with energy storage, but a broader category could include supplemental sources instead of storage. A base load system could be used by a single dwelling or small commercial or industrial establishment; or it could supply power to an entire community. A community system would require several medium to large sized installations. The base load approach may be necessary because the utility is inaccessible, or it may be chosen as a substitute for the utility.

Site Selection

The selection of a site for the windmill is as much a factor in determining the energy output as the windmill design. An inefficient windmill placed on a very good windmill site is a more favorable combination than a very efficient windmill placed on a poor site. No matter how well the windmill is designed, it cannot produce energy that it does not absorb.

The site may be influenced by more than the average wind velocity, however. Proximity to the load must be considered and perhaps a compromise must be made in some situations to achieve the best overall economy. This holds true both for the geographic location and for the height of the windmill above the ground.

Generally, the wind velocity increases and its turbulence decreases as the height above the ground increases. For instance, over an unobstructed plain, the wind velocity v at height H may be estimated from velocity v_0, measured at height H_0, from the relationship

$$\frac{v}{v_0} = \left(\frac{H}{H_0}\right)^n \quad (1)$$

where n = ½ for wind under 2 meters per second, n = 1/5 from 2 to 16 meters per second, and n = 1/7 above 16 meters per second.[5] However, the cost of a large tower to get a small windmill into the faster wind must be evaluated.

Meteorological Records

Meteorological data is helpful and it is easy and inexpensive to obtain. This information will tell where the wind is, what its prevailing direction is, how it varies from year to year and from month to month and also how the wind varies during the day.[6] There are two shortcomings of this information for selecting windmill sites, however. This data is recorded for the general purpose of keeping historical

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[5]E. N. Fales, "Windmills," Mark's Standard Handbook for Mechanical Engineers, 7th ed., (New York: McGraw Hill Book Co., 1967), p. 9-13.

[6]E. W. Golding, "Methods of Assessing the Potentialities of Wind Power on Different Scales of Utilization," International Seminar on Solar and Aeolian Energy, Sounion, Greece, Sept. 4-19, 1961, (New York: Plenum Press, 1964), p. 155.

data and for aiding in weather forecasting. Its form may not be suited for determining potential energy sites. Second, the wind measuring instruments are not located with the thought of selecting a windmill site. They are located for the convenience and purpose of the weather service.

The differences between the average wind speed at a weather station and the speed at a potential site just a few kilometers away can be significant from an energy standpoint. It will be shown later that the energy in the wind is proportional to the cube of the wind velocity. If a site is chosen that ultimately proves to have a lower average wind speed than the meteorological records indicate, then the available energy is cut drastically. A reduction in wind speed from 12 to 10 meters per second will reduce the energy in the wind 42%.

Aerodynamic and Ecological Criteria

Several things were learned about the relationship between the wind and the terrain during the Smith-Putnam Project. So far as aerodynamic criteria are concerned, Putnam and associates found no analogy between the profiles of mountains and the profiles of airfoils by which mean wind velocities could be predicted within useful limits. In fact, they could not even establish a basis for arranging windmill sites in an order of merit.[7]

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[7]Putnam, pp. 94-95.

An ecological yardstick was developed for use in the Green Mountains and the White Mountains of New England for estimating the long term mean annual wind velocity by observing the deformation of the trees. There is no reason to doubt that ecological criteria would permit arranging windy sites in any timbered area in an order of merit. However, Putnam had no way of guaranteeing that the same scale values developed in New England would apply to other regions.[8]

Trees can be deformed by many things: temperature, altitude, insects, disease, lightning, salt spray, abrasive particles in the wind, ice, protection by snow drifts, exceptionally high, but infrequent winds, and the habitual winds. Some training is necessary in order to identify the deformation caused by the habitual or mean wind and ignore the other deformations.[9] Five types of deformation can be listed in ascending mean wind velocity. Brushing is when the branches are bent leeward of the prevailing wind direction. Flagging is when the wind has caused the branches to stretch out to leeward, while the trunk is bare on the windward side, like a flagpole carrying a flag in a breeze. Throwing, or windthrown, is when the main trunk, as well as the branches, is deformed to the leeward. Wind clipping is caused by a severe enough wind to suppress the leaders of the tree and hold the tree tops to a common, abnormally low level.

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[8] Putnam, p. 95.

[9] Putnam, pp. 52-53.

Every twig which rises above that level is promptly killed. Tree carpets are formed where the wind is so severe as to prohibit upright growth while still allowing trees to start on the ground level. The result is a living carpet of prostrate branches spreading over the ground, ranging from 45 to 6 centimeters above the ground as the mean wind velocity increases. The critical value of the mean velocity, above which a tree cannot survive was found to be about 12 meters per second in the Green Mountains and White Mountains. Balsam experienced slight flagging at about 7.5 meters per second in those regions.[10]

The ecological measure of mean wind velocity is of an unknown accuracy, but it can be used to relate sites in order of merit, indicate which sites are of submarginal economic interest, and provide estimates of long-term mean annual velocity which may be accurate to the order of ± 20 percent.[11] Short of a wind study with instruments, the observation of deformed trees yields the most accurate appraisal of the potential windmill site.

Anemometer Study

Velocity measurements are the most accurate way to determine the wind power potential of a site. Also, unfortunately, it is the most costly method since it requires

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[10]Putnam, pp. 54-55.

[11]Putnam, p. 87.

the acquistion and installation of measuring and recording equipment; and it is a slow procedure since the mean annual velocity can only be obtained by measuring the velocity for an entire year.

The simplest device that can be employed is an inexpensive cup-counter anemometer which records the run-of-wind in kilometers. By reading the counter at appropriate intervals, and recording the amount of wind that has passed and the time, then the mean velocity between any two incidents of reading can be calculated.

A more informative installation is an electric contact type of cup anemometer and recorder giving hourly wind speeds. With this information the periods of calm can be determined as well as the estimated energy obtainable in a year.[12]

Detailed Design

The complete design of a wind powered generating installation must deal with six major components. They are the windmill, a generator, controls, an energy storage device, a tower, and power transmission equipment. The windmill, wind turbine, or other such device converts the kinetic energy of the wind into rotating mechanical energy. The major portion of this thesis will deal with this component. A generator converts the mechanical energy to electricity, or

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[12]Golding, "Methods of Assessing the Potentialities of Wind Power," p. 156.

another device may be used to convert the energy to a useful form. Generators and pumps have reached a high degree of development and reliability and this thesis will not attempt to add to it. Controls are needed to regulate the power output and since this operation is unique in some respects to wind power, it will be treated more thoroughly later. A means of storing energy is necessary in some installations. This component will also be discussed at some length. The last two components are the structure and power transmission equipment like gearboxes, bearings, belt drives etc. These are just an application of existing structural and mechanical engineering and no further development is required here.

CHAPTER II

THE COST OF ELECTRICITY

The production of electricity is essentially the same as the production of any product. Raw materials (fuel) are procured; processes are performed on the material to change it into a saleable product which requires the acquisition, operation, and maintenance of equipment; and the finished product is sold. The generation of electricity has some uniquenesses, but basically it has all the characteristics of any manufacturing operation; including a cost to produce the product.

There are basically two roles a wind power electric generation plant can play in the operation of an electric utility. With a storage system it can act as a competitor to the conventional system. A conventional system is any system that is used extensively for generating large quantities of electricity on demand. This definition usually limits the systems to hydroelectric, fossil fuel, or nuclear produced electricity, but not always, since geothermal or other systems may be considered conventional in some regions. Without a storage system and used by the utility company, it can act as a fuel saver.

Six items make up the total cost of electricity. They are: 1) capital cost of the plant, 2) fuel cost, 3) operating cost, 4) maintenance cost, 5) transmission cost and

6) distribution cost. When it is desirable to compare the cost of generating electricity by different power generation plants only the first four cost items need to be considered since transmission and distribution are outside the scope of the generation plant.

The cost of generating electricity can be calculated by the "busbar cost" equation. Busbar cost is expressed in mills per kilowatt hour such that

Busbar cost =

$$\frac{\begin{pmatrix}\text{Capital}\\\text{Cost}\end{pmatrix}\begin{pmatrix}\text{Fixed}\\\text{Charges}\\\text{\% yr.}\end{pmatrix}+\begin{pmatrix}\text{Fuel}\\\text{Cost}\end{pmatrix}+\begin{pmatrix}\text{Operating}\\\text{Cost}\end{pmatrix}+\begin{pmatrix}\text{Maintenance}\\\text{Cost}\end{pmatrix}\times 10^{3}\ \frac{\text{mills}}{\$}}{\text{Plant rating (kw)} \times \text{Load factor (\%)} \times 8760\ \text{(hr/year)}} \qquad (2)$$

Fixed charges are made up of the interest on the debt, the dividends on the equity, taxes, insurance, and depreciation. For a plant with a life expectancy of 30 years the fixed charges would be approximately 17%. The load factor is the ratio of the energy that was actually generated to the energy that could have been generated if the plant ran at full rating for the entire year.[13]

For conventional generating plants, a load factor less than one is due to the unsteady demand for electricity over the course of a day. These plants are assumed to have an adequate supply of fuel and the generating equipment has ample rating to meet the highest demand placed upon it. During the periods when the demand for electricity is below the

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[13] McCarthy, pp. 218-219.

plant rating, the generator is cut back. Typical load factor for a fossil fuel plant is 70%.

However, for any plant whose energy source is free but erratic, such as wind power or solar power, the load factor is a function of the supply of energy. The plant rating of these nonconventional power plants is based on the average supply of power. At any time this supply can drop below the value required to run the plant at full rating in which case the output is less than plant rating. If the generated power is fed into a storage device, the generator can continue to feed the storage device, regardless of the demand level and assuming the store is not filled. If the power is supplied to a power network, the conventional generators will be cut back when the demand is reduced, not the wind or solar plant, in order to reduce fuel consumption.

The wind velocity that corresponds to the wind power plant rating is called the "rated wind velocity" and its value is used to indicate the size of the wind power plant. If the wind velocity increases to more than the rated wind velocity of a plant, the amount of generated electricity is not increased, even though there is more energy available in the faster wind. More electricity could be generated by increasing the plant rating, but the higher rating will also be more costly. In each wind profile there is a practical limit above which the additional cost for more generating capacity outweighs the additional energy that can be captured during the small amount of time the wind speed exceeds that limit. More specifically, if the cost per kilowatt of rated capacity increases more rapidly than the energy output per kilowatt of rated capacity, then the cost per unit energy output will increase.

All the costs that appear in the busbar cost equation apply to wind powered plants except the fuel cost. The use of wind plants cannot even reduce the capital, operating, or maintenance costs of conventional generating equipment when both types are used to energize a large network. Since the wind is somewhat unreliable as an energy source, sufficient conventional generation capacity will have to be installed to meet anticipated loads. In this case, the economic value of wind powered plants is determined by the cost of the fuel replaced. When comparing the costs of wind systems used as fuel savers to that of conventional systems, the busbar cost of the electricity generated by the wind must be compared to the fuel cost of conventional sources.

To analyze wind systems for base power applications the cost of storage must be included in the busbar cost as part of the capital cost. The storage cost will vary with the storage capacity. Storage capacity is determined by the load and by the average length of calm spells when the storage device is not being charged.

For economic competitiveness, attention to both design and site location must be given. The design can effect cost in the following ways: The blade design determines the power coefficient, or the percentage of wind energy that is transformed into mechanical energy. However, a point is reached, as the blade design is improved, where the improvement in performance per dollar spent to make the blade begins to decrease very rapidly. A balance should be established between the lesser cost to produce a short blade and the greater cost to produce an efficient blade in order to produce the desired output. Secondly, the operating cost of the plant can be decreased by using automatic control of the operation. Third, low maintenance requirements can be obtained by specifying low maintenance components and weather resistant materials. Last, the initial capital cost is effected by the overall design. Economy in one area may increase cost in another. For example, weather resistant materials, say stainless steel, will reduce maintenance costs but will add to the capital cost.

The selection of the installation site determines the yearly energy output. The wind velocity at a site determines the potential power in the wind, and the design determines the swept area of the blades and the choice of rated wind velocity.[14]

The busbar cost is convenient, but another costing method gives a more complete cost. This is a type of life-cycle cost-accounting measure which includes environmental impact costs. This cost is becoming more and more prefer-

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[14] J. Peter Le Boff, "Wind Power Feasibility," Energy Sources, Vol. 2, No. 4, (1976), 364.

able due to the ecological considerations that are gaining attention. Wind systems would be expected to be more cost competitive with the latter costing technique because of their minimal ecological impact.[15]

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[15] Le Boff, 366.

CHAPTER III

WINDMILL

Propeller Type

Main Features

The basic design of the propeller type windmill features two, three, or possibly four long slender blades operating at a high ratio of blade tip speed to wind speed.[16] Among the forces acting on these blades are the gravitational pull of the earth, the wind pressure, and centrifugal forces. Several design features can be employed which affect the ability of the windmill to do its job while dealing with the forces acting upon it.

Ability to Spill Power

Winds of gale-force velocity can damage windmills, generators, and power transmission equipment if they are allowed to accelerate the windmill beyond a reasonable limit and transfer more power to it than the components can safely handle. To overcome this, a greater portion of the power in very high winds must be prevented from being transferred to

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[16] Boeing Vertol has proposed a one bladed windmill balanced by a low-cost counterweight. Black, "Something in the Wind?", 26.

the windmill. This nonacceptance, or spilling of power, should start to take place just below the rated capacity of the windmill and should limit the power input to below that point. It is usually necessary to completely stop accepting power when the velocity becomes too high.

One method for spilling power results from reducing the area of the windmill normal to the wind. This is done by swinging the windmill disc around the vertical axis until it lays parallel to the wind. The same results can be achieved by swinging the disc around a horizontal axis so that it becomes parallel to the ground as shown in Figure 1.[17]

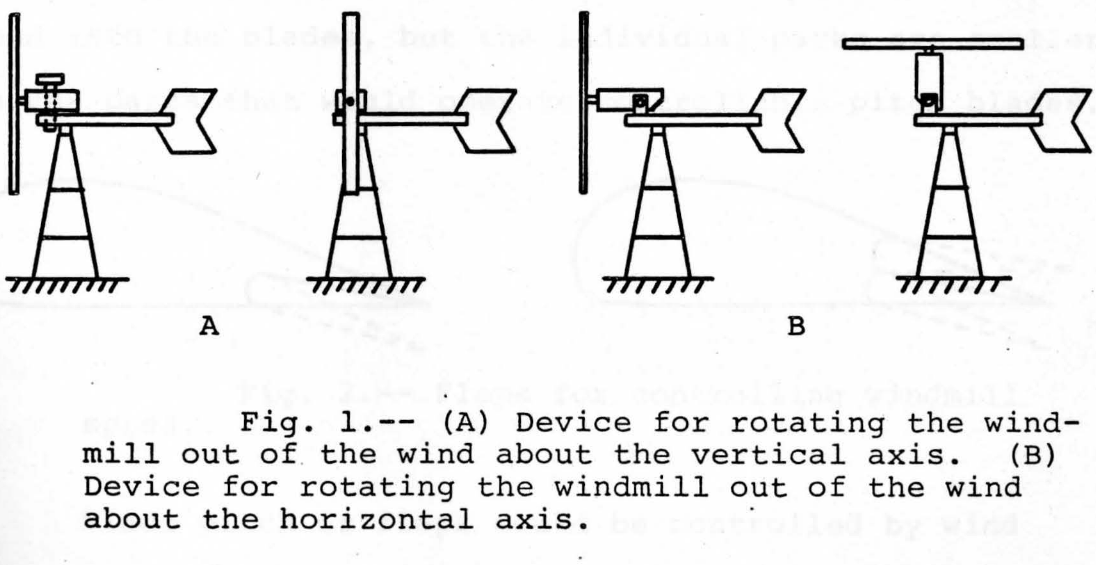

Fig. 1.-- (A) Device for rotating the windmill out of the wind about the vertical axis. (B) Device for rotating the windmill out of the wind about the horizontal axis.

Energy can also be spilled by reducing the efficiency of the blades by feathering them to a position of low lift and minimum drag. This design has a quicker response

[17] Putnam, p. 109.

to wind gusts due to the lower inertia of the adjustable parts. If windmill speed is going to be regulated by controlling the blade pitch, then the mechanism for feathering can be an extension of the means for pitch control.[18]

Another method of controlling input power is by reducing the aerodynamic efficiency of the blade by the use of flaps such as the one illustrated in Figure 2.[19] The use of controllable flaps, as opposed to controllable pitch, simplifies the attachment of the blades to the shaft, since there is no relative motion between them. This region of the blade is one of high stress concentrations and the elimination of moving parts from this area is very helpful. The operating machanism does become more complex and must extend into the blades, but the individual parts are smaller than the parts that would operate controllable pitch blades.[20]

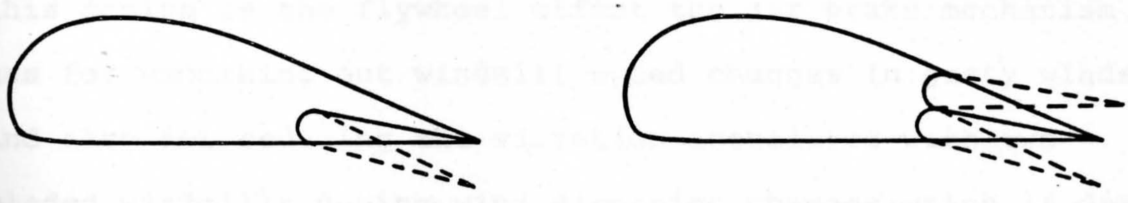

Fig. 2.-- Flaps for controlling windmill speed.

Blade pitch or flaps could be controlled by wind speed sensing devices such as a hinged plate held normal

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[18]Putnam, p. 109.

[19]Putnam, p. 111.

[20]Putnam, p. 202.

to the wind by a spring and attached to appropriate linkage, by a centrifugal fly-ball governor, or by some form of electronic torque or speed sensing apparatus.

A pair of air brakes are used to dissipate the wind power in high winds on one commercially available windmill. The flaps are hinged to arms extending from the windmill shaft and are held in position by springs. The axis of the hinges are parallel to the windmill shaft axis. The brakes rotate between the blades, and present only their edges to the relative wind at speeds within the safe operating range. When the wind speed increases to dangerous levels, the centrifugal force on the brakes overcomes the spring tension and they open to present their area to the direction of rotation as shown in Figure 3. This causes turbulance in the wind that contacts the windmill blades. An added advantage of this design is the flywheel effect the air brake mechanism has for smoothing out windmill speed changes in gusty winds, and also for reducing the vibration associated with two bladed windmills during wind direction changes which is discussed more fully in the next section.[21]

[21] Advertising bulletin, Form No. D181, Winco, Division of Dyno Technology, Inc. Sioux City, Iowa.

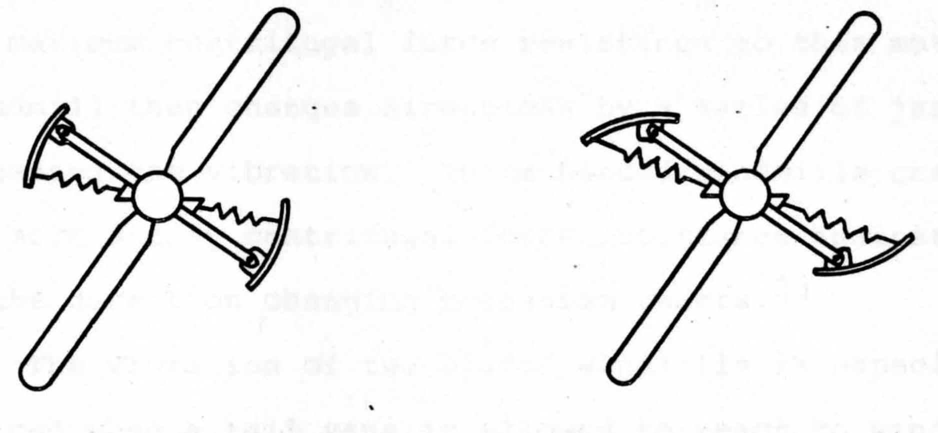

Fig. 3-- Schematic of air brake.

Number of Blades

The power of a three or four bladed windmill will exceed the power of one with two blades, assuming the diameter and blade sections are the same for each. When the windmills operate at their most favorable tip speed ratio, the difference is only a few percent. Below the most favorable tip speed ratio, a considerably greater efficiency is obtained by three or four blades than by two blades, although the difference is not proportional to the number of blades.[22]

When a two bladed windmill shifts to follow changes in the wind direction, serious vibrations are introduced. When the blades are in a vertical position, they offer no

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[22] J. Juul, "Wind Machines," Wind and Solar Energy, Proceedings of the New Delhi Symposium, (Paris: United Nations Educational Scientific, and Cultural Organization, 1956) p. 62-63.

centrifugal force resistance to movement around the vertical pivot axis. However, in the horizontal position, the blades have a maximum centrifugal force resistance to this motion. The windmill then changes directions by a series of jerks which causes the vibration. Three bladed windmills create a much more steady centrifugal force resistance against which the direction changing mechanism reacts.[23]

The vibration of two bladed windmills is especially pronounced when a tail vane is allowed to react to wind direction changes very quickly. If damping is used on this movement, or if the windmill is oriented slowly by a servo mechanism driving a motor, the vibration is not as great a problem.

Generally the increased power of three or four blades is not worth the expense of the added blades, but the problem of vibration must be dealt with.

Coning

Coning of windmill blades is the tilt out of the plane perpendicular to the shaft.[24] Positive coning is when the blades tilt down wind. The purpose of coning is to reduce the stress at the root of the blades caused by the wind

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[23] Marcellus L. Jacobs, "Experience with Jacob's Wind Driven Electric Generating Plant, 1931-1957," Proceedings of The United Nations Conference on New Sources of Energy - Wind Power, Rome, Aug. 21-31, 1961, Vol. 7 (New York: United Nations, 1964), p. 337

[24] Some literature refers to coning as a teetered hub.

pressure on the blades. The bending moment from the wind is balanced by the centrifugal force moment of a coned blade.

Blades can either have a built-in fixed coning angle or they can be hinged to freely seek their optimum coning angle for the conditions at hand. The amount of coning of hinged blades is a result of the instantaneous wind pressure, the centrifugal force, the angular momentum of coning, and any coning damping that may be applied.[25]

The Smith-Putnam Wind-Turbine was built with provisions for heavy coning-damping. Through testing it was discovered that as the damping constant was reduced the operation of the unit became much smoother. This conclusion was reached by measuring the yawing moment and pitching moment for various amounts of damping. The yawing moment is the result of the forces which tend to cause motion in a horizontal plane, or about the vertical pivot axis of the windmill. Pitching moment is used in the nautical sense of the word pitch. It is from the forces causing motion in the vertical plane about a horizontal axis parallel to the plane of rotation.[26]

Yaw

Yaw is the horizontal motion around the pivot axis and it is needed to allow the blade disc to stay normal to

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[25] Putnam, p. 111.

[26] Putnam, p. 203.

the wind. Small windmills can easily be oriented to the wind by means of a tail vane. The action of the wind on a tail vane causes the vane to move to the downwind position. Large, heavy windmills would require a large tail vane on a long arm. This approach is usually abandoned for large windmills in favor of a small yaw vane controlling a servo-mechanism and a yaw motor to turn the windmill through appropriate gearing.[27]

Yaw is made possible by a pintle shaft and bearings. The pintle shaft is a vertical shaft that supports the entire horizontally rotatable structure. The pintle shaft turns in, and is supported by, radial and thrust bearings in the top of the windmill tower.

Relative Position of Windmill and Tower

The windmill can be designed to operate either upwind or downwind of the tower. From the standpoint of power, the downwind style would seem to have a slightly smaller output than the upwind style if all other design features were the same. This difference would be the result of the tower blocking out a small portion of the wind falling on the windmill disc and also causing some turbulence in the area behind the tower. Whether this shadow effect is significant is not known, however. No sources of information were found that explored this question.

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[27] Putnam, p. 113.

The blocking of the wind by the tower causes another, more important problem in the downwind windmill: vibration. As the blades travel through this wind shadow once each revolution the relatively steady wind pressure on the blades is interrupted. This cyclic loading, equal in frequency to the angular velocity in revolutions per second, causes blade vibrations. On the other hand, an upwind windmill will reverse this effect and cause an interruption of the wind pressure on the tower. This frequency of load on the tower is equal to the number of blades times the revolutions per second of the windmill. Whichever design is used, the natural frequency of the downwind component must not approach the frequency of the cyclic loading or the amplitude of the resulting vibration will quickly build to the point of damaging the equipment.

Tower shape and the use of coning can play a large role concerning the relative position of the tower and windmill. Due to its cantilever beam type of arrangement, the tower is subject to a greater bending moment at its base. Therefore, the usual shape of the tower will be wide at the base and narrow at the top.[28] If the windmill is located upwind of the tower, the windmill shaft will have to have enough overhand to allow the blades to clear the sloping tower legs plus enough to allow for blade flexing. If

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[28] A study was made as part of the Smith-Putnam Wind-Turbine project to determine the most economical slope of tower legs. The value was determined to be 8 degrees from the vertical. Putnam, p. 113.

coning is employed, the overhang will have to be increased to allow for this also. By mounting the windmill downwind of the tower the shaft overhang can be reduced, and more importantly the bending moment can be reduced. Shaft overhang is depicted schematically in Figure 4.

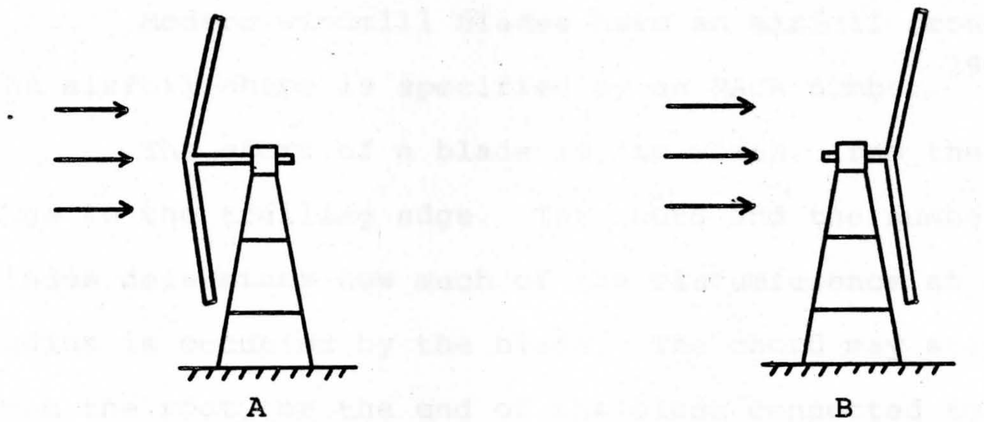

Fig. 4-- Comparison of the shaft overhang required for (A) upwind windmills and (B) downwind windmills with coned blades and sloping tower legs.

The arrangement of the blades located downwind of the tower is a more stable one than having the blades upwind. The blades themselves tend to act like a tail vane in the wind.

The Smith-Putnam Wind-Turbine and most other large windmill installations that are operating or are being planned have chosen the blades to be downwind. Reasons for this approach are given as reduced shaft overhand, the desire to avoid cyclic loading on the tower in preference to the blades, and yaw stability. Small windmills available commercially, both in the past and today, seem to prefer upwind blades and the use of long tail vanes to control yaw.

Blade Size and Shape

The blades of the windmill are the components that are responsible for converting the power in the wind to usable mechanical power. A few terms and characteristics will be described here.

Modern windmill blades have an airfoil cross section. The airfoil shape is specified by an NACA number.[29]

The chord of a blade is its width, from the leading edge to the trailing edge. The chord and the number of blades determines how much of the circumference at any given radius is occupied by the blade. The chord may stay constant from the root, or the end of the blade connected to the shaft, to the tip; or the chord may vary giving a tapered blade.

The chord line of a windmill blade does not lie parallel to the plane of rotation. A blade angle, defined as the angle between the chord line and plane of rotation, is necessary to get the intended results. The pitch is expressed in degrees and may be constant for the entire blade length or it may vary to give the blade a twist. If the blade does have a twist, the pitch is small at the tip and increases as the distance to the root is approached in a properly designed blade.

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[29] NACA stands for National Advisory Committee for Aerodynamics, a United States Agency.

Aerodynamics

The power in the wind can be determined by using the concept of kinetics. The kinetic energy of a particle equals one half the mass of the particle times the square of its velocity. The mass of the wind is equal to the density of the air times its volume. By restraining our exercise to the wind passing through a control area the velocity of the wind times the area will give volume per unit time, or volume flow rate, "Q". The introduction of 1/time on the other side of the kinetic energy equation changes energy to power.

$$\frac{E_K}{t} = \frac{\frac{1}{2}mv^2}{t} = \tfrac{1}{2}(\rho Q)v^2 = \tfrac{1}{2}(\rho Av)v^2;\ \text{or,}$$

$$P = \tfrac{1}{2}\rho Av^3 \qquad (3)$$

where P is the power in the wind passing through an area A with a velocity v; and, ρ is the density of the air.[30]

The windmill operates in an unconfined fluid. As the wind passes through the disc of the windmill it is slowed down and energy is transferred to the windmill. The column of air is expanded as it passes the machine. The pressures p_1 and p_4 at some distance ahead of and behind the windmill as shown in Figure 5, and the pressures over the slipstream boundary are the same. The only force acting in the slipstream is that exerted on the windmill.

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[30] Putnam, p. 88.

This force can be computed from the pressure difference (p_2-p_3) such that

$F = A_2p_2 - A_3p_3 = A(p_2-p_3),$ (4)

assuming $A_2 = A_3 = A$. This force can also be computed from the loss of momentum between sections 1 and 4 by

$F = \dot{m}_1v_1 - \dot{m}_4v_4,$ (5)

where $\dot{m}$ is the mass flow rate. By the conservation of mass $\dot{m}_1 = \dot{m}_4 = \rho Av_p$, so the equation becomes

$F = \rho Av_p \ (v_1-v_4).$

Combining equations (4) and (5) and dividing out the A's, yields $p_2-p_3 = \rho v_p \ (v_1-v_4).$ (6)

By applying the Bernoulli principle between sections 1 and 2 and between sections 3 and 4, and by using $p_1 = p_4$, another expression for (p_2-p_3) is derived. The equations $p_1 + \frac{1}{2}\rho v_1{}^2 = p_2 + \frac{1}{2}\rho v_p{}^2$ and $p_3 + \frac{1}{2}\rho v_p{}^2 = p_4 + \frac{1}{2}\rho v_4{}^2$ are derived by the Bernoulli principle and when combined will give:

$p_2-p_3 = \frac{1}{2}\rho(v_1{}^2-v_4{}^2).$ (7)

Equating equations (6) and (7) yields the velocity through the windmill disc is the numerical average of the velocities at some distance upstream and downstream.

$$v_p = \frac{v_1 + v_4}{2} \qquad (8)$$

The velocity of the wind is diminished at the windmill by an amount known as the interference factor, "a." From equation (8) the velocity diminishes ultimately by "2a" behind the windmill.

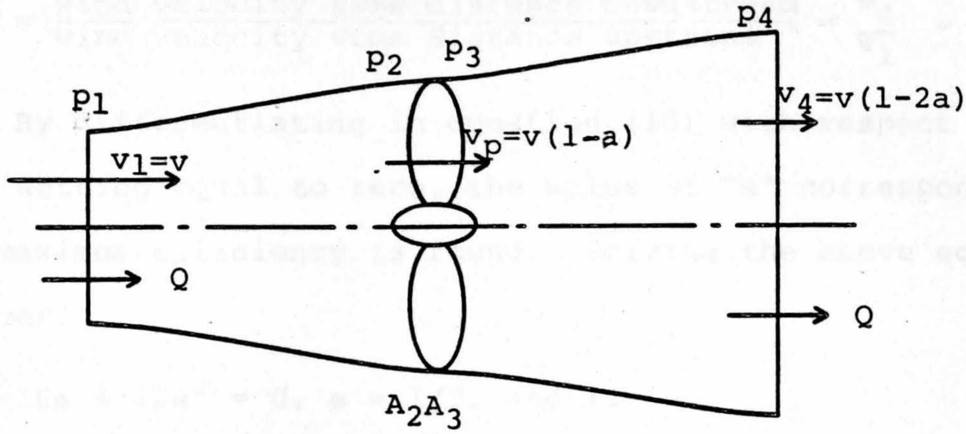

Fig. 5--Expansion of air stream through a windmill.

In a frictionless machine, the power transferred to the windmill equals the decrease in the power of the wind passing through it. This is the output power of the windmill and is derived as follows:

$$P_o = \tfrac{1}{2}\dot{m}\,(v_1{}^2 - v_4{}^2) = \tfrac{1}{2}\rho A v_p (v_1{}^2 - v_4{}^2)$$

$$P_o = \tfrac{1}{2}\rho A v(1-a)\left[v^2 - v^2(1-2a)^2\right] \qquad (9)$$

The efficiency of the power a windmill can extract from the wind is the ratio of the power transferred to the windmill to the power available in the wind through area A and with velocity v.

$$\eta = \frac{P_o}{P} = \frac{\tfrac{1}{2}\rho A v(1-a)\left[v^2 - v^2(1-2a)^2\right]}{\tfrac{1}{2}\rho A v^3} = 4a(1-a)^2 \qquad (10)$$

This efficiency, called the axial power coefficient, can also be expressed in terms of the decreasing factor or reduction coefficient, γ.

$$\eta = \tfrac{1}{2}\left[1 + \gamma - \gamma^2 - \gamma^3\right], \qquad (11)$$

where $\gamma = \dfrac{\text{wind velocity some distance downstream}}{\text{wind velocity some distance upstream}} = \dfrac{v_4}{v_1} = 1-2a$

By differentiating in equation (10) with respect to "a" and setting equal to zero, the value of "a" corresponding to the maximum efficiency is found. Solving the above equation gives

$\dfrac{d\eta}{da} = 4-16a + 12a^2 = 0$, $a = 1/3$, and 1.

For a = 1/3, the maximum theoretical power that a windmill can extract from the wind is 16/27 or 59.3% which is known as the "Betz limit" after Von A. Betz of Germany.[31]

The velocity of an element of the windmill blade is the product of the circumference of the circle traced by the element and the rotational speed of the windmill, and is denoted by V so that

$$V = 2\pi r \omega, \qquad (12)$$

where r is the radius to the blade element and ω is the rotational speed in revolutions per second.

The blade velocity and wind velocity vectors combined give the relative wind velocity, v_r, which is the wind velocity vector that the moving blade element experiences. The relative wind velocity intersects the plane of rotation at angle ϕ , as shown in Figure 6, and produces on the blade a lift force, L, perpendicular to v_r and a drag force,

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[31]John F. Vennard and Robert L. Street, Elementary Fluid Mechanics, (New York: John Wiley & Sons, 1975), pp. 250-253.

D, parallel to v_r. The resultant of the lift and drag forces, R, can be split into two other components. The thrust, T, is perpendicular to the plane of rotation, and tends to overturn the windmill installation, and the driving or torqueing force, F_Q, which is parallel to the plane of rotation, and does the useful work.

$T = L \cos\phi + D \sin\phi = L \cos\phi [1 + K \tan\phi]$

$F_Q = L \sin\phi - D \cos\phi = L \sin\phi [1 - K \cot\phi]$, where $K = D/L$.

Since the windmill is not a frictionless machine as was assumed when equation (9) was derived, the useful power given to the machine is $F_Q \times V$, while the power taken from the wind arriving at the machine is Txv. The efficiency of the windmill can be shown as the power coefficient, C_p.

$$C_p = \frac{F_Q x V}{Txv} = \frac{1-K\cot\phi}{1+K\tan\phi} = \frac{1-K\ V/v}{1+Kv/V} \qquad (13)$$

since $V\sin\phi = v\cos\phi$. The efficiency thus depends upon K and V/v. Efficiency would be low if V/v were very large or again if V/v were very small. In practice V/v is large in modern windmills so only the first of these possibilities must be considered.[32]

The axial thrust, or the force which tends to overturn the windmill, is equivalent to the decrease in the force of the wind passing through the windmill disc. The velocity of the wind is decreased by 2va. The thrust is found by

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[32] E. W. Golding, The Generation of Electricity by Wind Power, (London: E. & F.N. Spon Limited, 1955) pp. 199-200.

using a variation of the relationship force equals mass times acceleration; ie,

$$T = \Delta F = \dot{m}(\Delta v) = [\rho Av(1-a)] \times [2va] = 2\rho Av^2a(1-a). \quad (14)$$

By differentiating with respect to "a" and setting equal to zero the value of "a" which yields the maximum thrust is established.

$$\frac{dT}{da} = 2\rho Av^2(1-2a) = 0; \; a=\tfrac{1}{2}.$$

At a = ½, the thrust is:

$$T_{max} = \tfrac{1}{2}\rho Av^2.^{33} \quad (15)$$

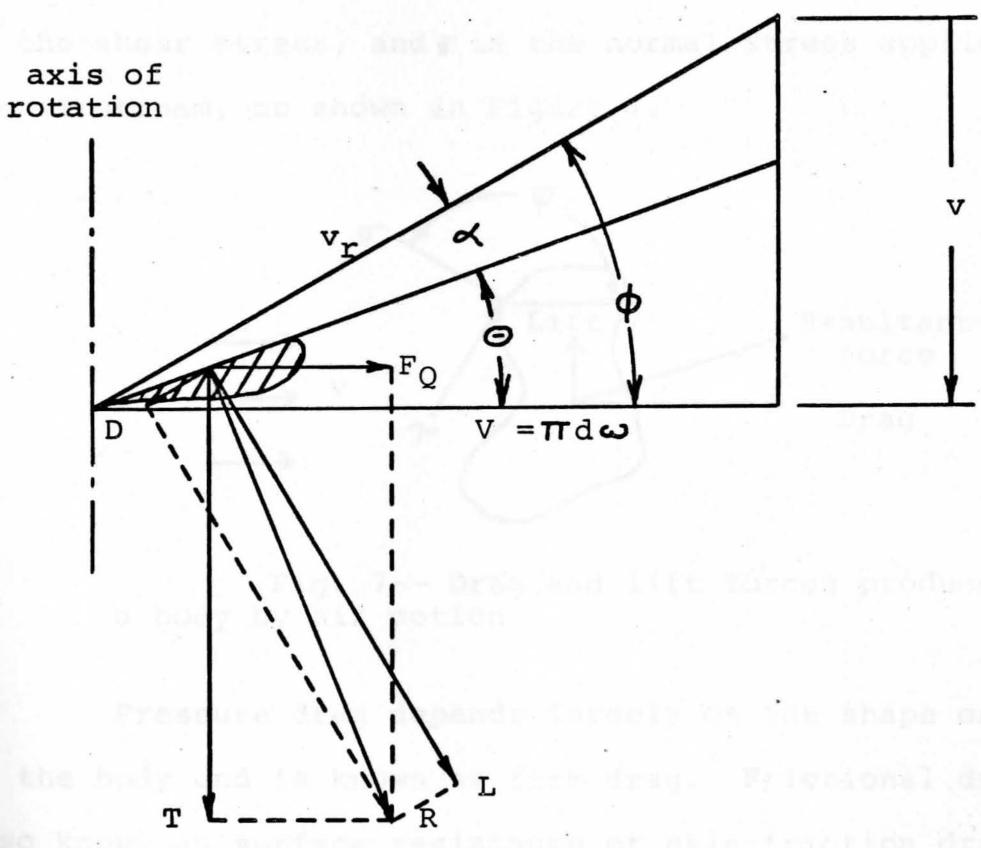

Fig. 6-- Forces that result from the action of the relative wind on a windmill blade.

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[33]Golding, The Generation of Electricity by Wind Power, p. 193.

The force, $\frac{1}{2}\rho Av^2$, can be used to define the lift coefficient C_L and the drag coefficient C_D.[34]

The total drag of a body in an airstream is composed of the frictional drag,

$D_f = -\int_S \tau \sin\psi \, dS$;

and the pressure drag,

$D_p = \int_S \sigma \cos\psi \, dS$,

to give $D = D_f + D_p$.

S is the total surface area, ψ is the angle between the normal to the surface element and the air flow direction, τ is the shear stress, and σ is the normal stress applied by the airstream, as shown in Figure 7.

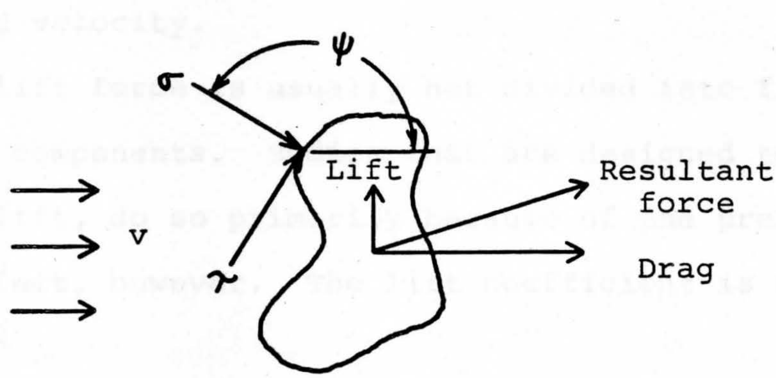

Fig. 7-- Drag and lift forces produced on a body by air motion.

Pressure drag depends largely on the shape or form of the body and is known as form drag. Frictional drag is also known as surface resistance or skin-friction drag. Bodies like airfoils have large and sometimes completely

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[34] Golding, The Generation of Electricity by Wind Power, p. 199.

dominant surface resistance. The surface resistance depends upon the finish of the blade surface.

The drag coefficients are defined by

$$D_f = C_f \tfrac{1}{2}\rho A_f v^2$$

and $D_p = C_{Dp} \tfrac{1}{2}\rho A_p v^2$

where A_f is the area over which the shear stresses act or the platform area of an airfoil and A_p is the frontal area normal to v. The total drag coefficient for the windmill blade is defined by

$$D = C_D \tfrac{1}{2}\rho A v_r^2, \tag{16}$$

where $C_D = C_{Df} + C_{Dp}$, $A = A_p$, $C_{Df} = C_f\ (A_f/A_p)$ and v_r is the relative wind velocity.

The lift force is usually not divided into frictional and pressure components. Bodies that are designed to produce useful lift, do so primarily because of the pressure component effect, however. The lift coefficient is defined by

$$L = C_L \tfrac{1}{2}\rho A v_r^2 \tag{17}$$

where A is the frontal area of the airfoil normal to v_r.[35]

These coefficients can be determined experimentally for any profile and are found to vary with the angle of attack, α. Due to the dependence of the surface resistance on the surface finish, the drag data obtained from experimental measurements on airfoils are subject to some uncertainty,

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[35] James W. Daily and Donald R. F. Harleman, Fluid Dynamics, (Reading, Mass.: Addison-Wesley, 1966), pp. 170-171.

however.[36]

Since v_r and ϕ are dependent upon V, and since V is directly proportional to r, then for a constant wind speed distributed uniformly over the rotor surface both the magnitude and the direction of v_r will vary with r. Since the lift is dependent upon v_r, then the useful lift per unit of blade surface will also vary with r.

Equation (13) implies that to have high efficiency the blade sections must have great lift and small drag. The lift for a given profile increases with increasing angle of attack until it reaches its stalling value, after which the lift decreases.

To extract optimum power from each succeeding blade section the angle the blade makes with the plane of rotation, θ, must vary with the radius to suit the changing direction of the relative wind. This is required to keep each element near the optimum angle of attack. It follows, therefore, that to maintain the best angle of attack, the blade angle should vary continuously along the blade and should be greatest at the root and least at the tip.

If the angular velocity of the windmill does not vary with the wind velocity then the angle of attack will vary. The power coefficient of the rotor thus varies with the relationship between the rotational speed and the wind speed.

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[36] Golding, The Generation of Electricity by Wind Power, p. 199.

This relationship is most conveniently expressed for any given blade design in terms of the tip speed ratio, μ, defined by:

$$\mu = \frac{V_{tip}}{v} = \frac{2\pi R\omega}{v} \qquad (18)$$

where R is the radius to the blade tip. If the rotational speed of the rotor can be kept proportional to the wind speed optimum output is obtained. This is possible only to a certain degree in practice because, first, the inertia of the rotor is high and second, the wind speed can vary over the swept area.[37]

Bicycle Wheel Type

The American Wind Turbine Co. offers a bicycle wheel type windmill for sale which is also called a super speed turbine.[38] The School of Electrical Engineering at Oklahoma State University has chosen this type of windmill for their wind power studies and they use it in conjunction with their energy storage and electricity control studies.

The super speed turbine (SST) resembles a large bicycle wheel with a narrow rim connected to its axis by wire spokes. The spokes support light weight, aerodynamically

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[37] Golding, The Generation of Electricity by Wind Power, p. 207-208.

[38] Advertising bulletin, AWT Bulletin 76-1, American Wind Turbine Co., Stillwater, Oklahoma.

shaped blades.[39]

The construction is such that key structural members are in tension. When combined with the simple construction of the SST, this allows a very light and very strong structure. The blades are light enough so that no other bracing is required. The supporting tower for this system can be light weight and designed to be easily fabricated. As a result of these points, the cost of the SST is low.

Efficiency measurements have shown the SST to be favorably comparable to other designs of windmills.

The large and continuous rim of this windmill can be used to simplify the power take-off function. A flat belt drive can take the power from the rim to a much smaller pulley on the generator shaft. By doing this instead of the taking the power from the hub, the expense and weight of a gearbox is eliminated.[40]

Windmills up to 4.8 meters in diameter are commercially available, but there appears to be no difficulty scaling them up to larger sizes other than solving a few straight forward engineering problems.

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[39]Theodore W. Black, "Advanced Turbine Designs Boost Wind Power Potential," Machine Design, Vol. 48, No. 14, (June 10, 1976), 31.

[40]W. L. Hughes, et al, "Basic Information on the Economic Generation of Energy in Commercial Quantities from Wind," Hearing before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, No. 49, (Washington: U.S. Government Printing Office, 1974) p. 26.

Vertical Axis Type

Several versions of a vertical axis windmill are available or are under study at research sites in the United States and Canada. These units offer three important features for an economic design. They have high aerodynamic efficiency, secondly, they have a high blade speed to wind speed ratio, and they have a simple design.

A vertical axis windmill will accept wind from any direction without the need for any direction adjusting equipment. The electric generator can be located on the ground and driven without a right angle gearbox. The supporting tower can be greatly simplified since it does not have to carry the weight of a generator and gearbox aloft. In fact, most designs call for the vertical rotating shaft to be the only support and to use a bearing at the top attached to guy ropes to keep the structure upright. The airfoil shaped blades are of constant cross section. There is no advantage to producing a blade with a twist or a taper.[41]

A high speed windmill with straight rigid blades rotating parallel to the vertical axis will be subject to a high bending moment from the centrifugal force. Extra bracing will be needed to deal with this. This problem can be overcome by making the blade flexible, attaching the ends to the shaft with enough slack to allow the blade to bow and

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[41]Richard Stepler, "Eggbeater Windmill," Popular Science, May 1975, 74.

allowing the blade to seek its own shape as it rotates. Under the centrifugal force the blade would conform to an approximate catenary shape known as a tropeskien shape, which is a word derived from Greek meaning turning rope. Figure 8 shows the two types of vertical axis windmills. Bending stress is virtually eliminated since the blade was allowed to seek its own shape and only tensile stress is present in the blade. This stress is much easier to cope with. If the windmill blade is then preformed to a shape approaching the tropeskien, the bending stress will be negligible.[42] This style of vertical axis windmill is attributed to G.J.M. Darrieus of France and it carries his name: the Darrieus windmill.[43]

The optimum vertical axis windmill configuration would then be one with a constant chord blade, curved into a tropeskien and enclosing the maximum area for a given blade length. The swept area is a maximum for any given blade length when the diameter is equal to the height of the rotor.[44] The ends of each blade contribute little to the conversion of wind power to mechanical power. The center of the blade comprising 45 percent of the blade length produces approxi-

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[42] Peter South and Raj Rangi, "NRC's Vertical Wind Turbine," Agricultural Engineering, Vol 55, No. 2, (Feb. 1974), 15.

[43] Stepler, 74.

[44] South, 16.

mately 90 percent of the total power.[45] The height and diameter of the windmill is approximately 2/3 the length of one blade.[46]

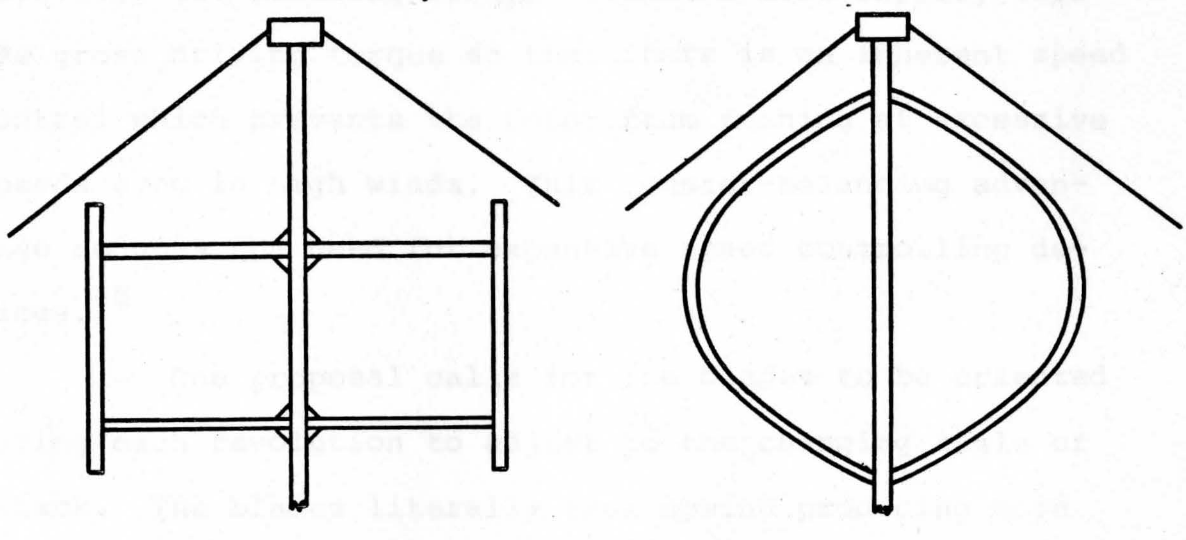

Fig. 8-- Vertical axis windmills (A), with straight blades, and (B) with tropeskien shape blades.

Extensive wind tunnel and field tests on vertical axis windmills by the National Research Council in Canada showed the power coefficient to be equivalent to that of a well designed propeller type windmill and the tip speed ratio associated with the maximum power coefficient to be in the range of five to seven.[47]

One disadvantage of the vertical axis windmill is

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[45]Stepler, 74.

[46]L. I. Weingarten and R. E. Nickell, "Nonlinear Stress Analysis of Vertical-Axis Wind Turbine Blades," Transactions of the ASME, Paper No. 75-DET-35, (Nov. 1975), 1235.

[47]South, 16.

that a portion of the blade motion is opposite the relative wind direction and some of the power must be expended to overcome this resistance. However, as the windmill speed increases the breaking torque increases more rapidly than the gross driving torque so that there is an inherent speed control which prevents the rotor from running at excessive speeds even in high winds. This counter-balancing advantage reduces the need for expensive speed controlling devices.[48]

One proposal calls for the blades to be oriented during each revolution to adjust to the changing angle of attack. The blades literally tack upwind producing more power. This kind of control is easy to provide in a straight bladed windmill, but is not easy to provide in the Darrieus type.[49]

The vertical axis windmill appears to be a vitally important contender to economical generation of power from the wind.

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[48] Golding, <u>The Generation of Electricity by Wind Power</u>, pp. 201-202.

[49] Black, "Advanced Turbine Designs Boost Wind-Power Potential," 31.

CHAPTER IV

CONTROL OF ELECTRICAL OUTPUT

Except for the Smith-Putnam Wind-Turbine, most windmills in operation prior to 1970 were small, less than ten kilowatt rating, and were used to pump water or to generate electricity in conjunction with battery storage. Recently, the questionable supply and the cost of energy fuels has raised interest in wind power generation of electricity on a large scale to be fed to existing power grid networks. The intermittency of wind power is not a serious problem in this circumstance since the network will have a capacity many times greater than the wind generating system. All the electricity generated by wind power can be used when it is available. When it is not available, other means provide the needed power.[50]

There is, however; another aspect of wind energy that does require attention. The windmill naturally rotates at a speed proportional to the wind speed, which varies greatly. Varying the speed of a usual alternating current (AC) generator with a direct current (DC) field excitation will produce

[50] T. S. Jaya Devaiah and Richard T. Smith, "Generation Schemes for Wind Power Plants," IEEE Transactions on Aerospace and Electronic Systems, Vol AES-11, No. 4, (July 1975), 543.

a varying frequency.[51] This is unsuitable for interconnection with a power network since the frequency in the networks must be maintained at a constant value: 60 hertz in North America, 50 or 60 hertz in most of the rest of the world.

Constant Speed-Constant Frequency

Since the frequency of electricity is partly determined by the angular velocity of the generator which produced it, the task of generating a constant frequency can be handled by rotating the generator at a constant speed.

The system used to maintain constant frequency by Putnam, and by the NASA 100 kilowatt windmill at Plum Brook, Ohio that is currently operating, was to vary the pitch or blade angle as the wind speed changed. This maneuver changes the efficiency of the blades as well as the tip speed ratio and results in a constant speed and constant power output regardless of the wind speed. The constant power is not essential to producing constant frequency electricity, but it accompanies this type of control. In fact, a great deal of tapable wind power is spilled by this method. Variable pitch

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[51] The field of a generator is the component that produces the magnetic flux that causes current to flow in a wire when the wire is moving through the magnetic flux. The component that contains the wires in which the current is induced is the armature.

does have advantages also. Response to wind speed changes is quick, and windmill speed can be controlled to a very accurate degree.[52]

Pitch Control

Several arrangements for varying blade pitch in response to wind speed have been used. One design is by means of a simple mechanism utilizing the blades themselves as a governor. The axis of the blade is set at an angle to the varying pitch axis which will produce a moment about the varying pitch axis due to the centrifugal force exerted on the blade by the windmill rotation. Figure 9 shows this angle labeled as the second tilting angle.

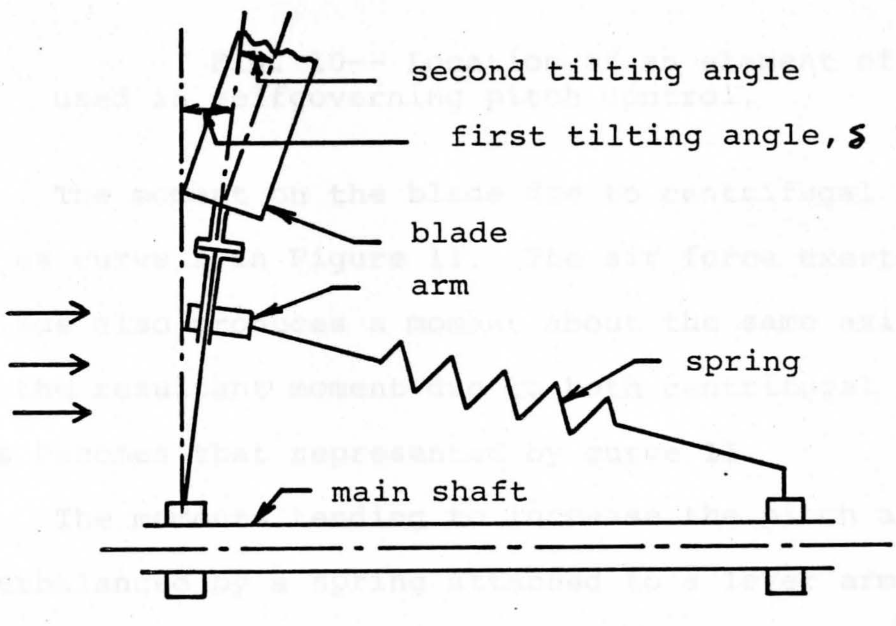

Fig. 9-- Schematic of mechanism for keeping the rotational speed constant.

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[52]Putnam, p. 110.

This moment is exerted in such a way that the angle β shown in Figure 10 will decrease. The blade can be set so that the moment acts to increase the pitch angle Θ.

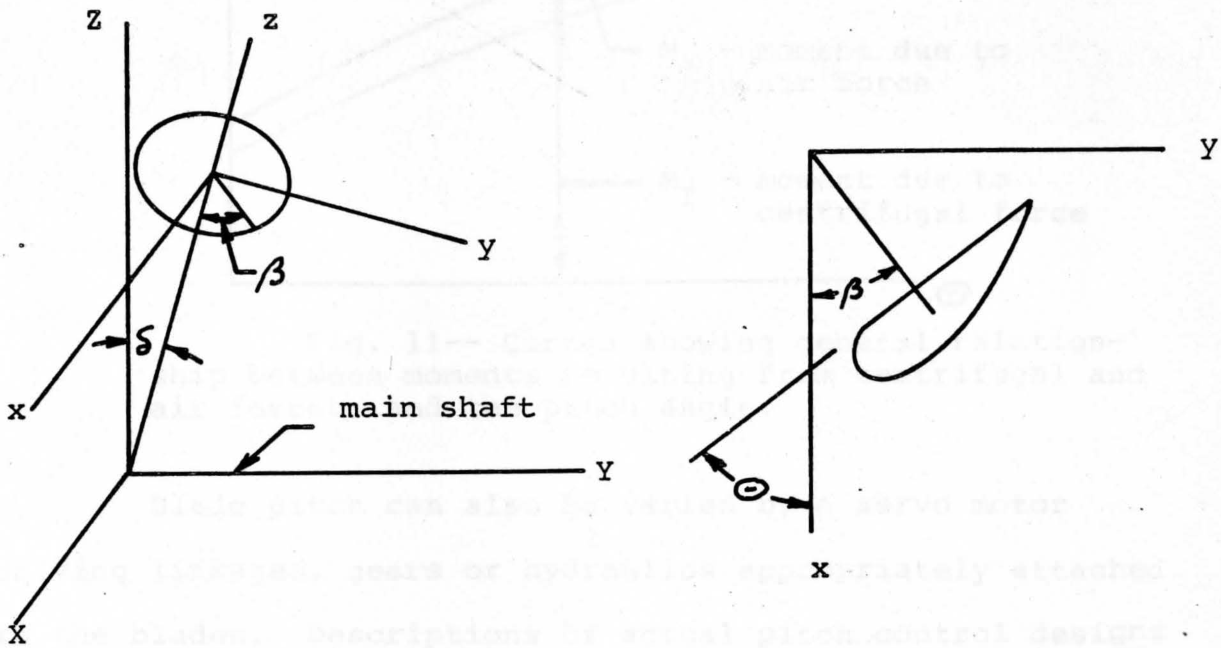

Fig. 10-- Location of an element of a blade used in selfgoverning pitch control.

The moment on the blade due to centrifugal force is shown as curve I in Figure 11. The air force exerted on the blade also produces a moment about the same axis. Therefore, the resultant moment due to both centrifugal and air forces becomes that represented by curve II.

The moments tending to increase the pitch angle are counterbalanced by a spring attached to a lever arm on the blade's varying pitch axis as shown in Figure 11. The spring force is applied to the blade through the whole range of Θ so that the windmill can operate at any pitch angle by balancing the moments one against the other.[53]

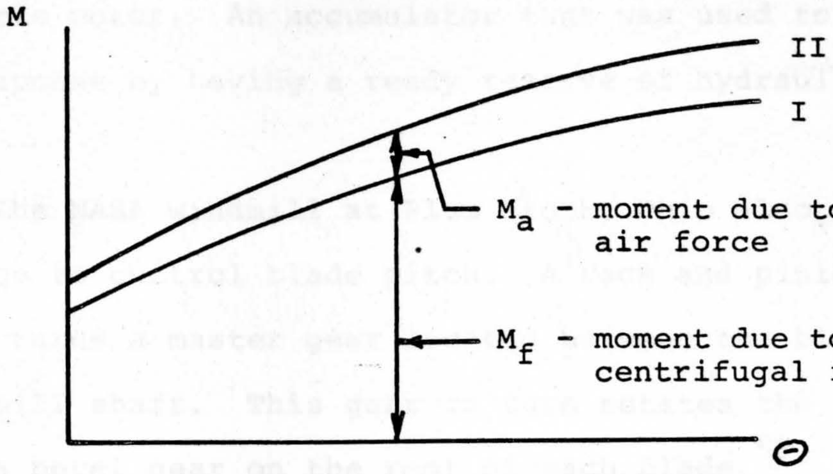

Fig. 11-- Curves showing general relationship between moments resulting from centrifugal and air forces, and the pitch angle.

Blade pitch can also be varied by a servo motor driving linkages, gears or hydraulics appropriately attached to the blades. Descriptions of actual pitch control designs can further explain this component.

The Smith-Putnam Wind-Turbine utilized a speed sensitive centrifugal fly-ball governor to control hydraulic circuits which activated a hydraulic pitching cylinder located inside the main windmill shaft. The pitching cylinder controlled the pitch of both blades through links, cranks, and torque tubes to the blade shanks which supported the blades and were free to rotate on antifriction bearings. The

[53]Tomijiro Moriva and Yoshio Tomosawa,"Wind Turbines of New Design in Japan," Proceedings of The United Nations Conference on New Sources of Energy - Wind Power, Rome, Aug. 21-31, 1961, Vol. 7, (New York, United Nations, 1964), pp. 249-250.

hydraulic oil pump could be driven by the windmill or by an electric motor. An accumulator tank was used to allow quick response by having a ready reserve of hydraulic pressure.[54]

The NASA windmill at Plum Brook, Ohio also uses hydraulics to control blade pitch. A rack and pinion type actuator turns a master gear located between the blades in the windmill shaft. This gear in turn rotates the blades through a bevel gear on the root of each blade.[55]

Another windmill that operated in the 1950's in the township of Haslev, Denmark for Sydoslsjaellands Elektricitets Aktieselskab (abbreviated SEAS), an electric power supply company, achieved constant rotational frequency by varying brake flaps at the ends of the blades. Except for the flaps, the blade pitch was not adjustable during the operation of the unit. A centrifugal fly-ball governor closed an electronic contact at the desired rotational frequency, which activated an electromagnetically governed regulator valve which in turn directed pneumatic pressure to an air cylinder. The motion of the cylinder caused the brake flaps to rotate by means of linkages in the windmill shaft and blades.[56]

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[54] Putnam, pp. 116-118.

[55] Ronald L. Thomas, <u>et al</u>, "Plans and Status of the NASA-Lewis Research Center Wind Energy Project," <u>Proceedings of the 2nd Energy Technological Conference</u>, NASA TM X-71701, Washington, May 12-14, 1975, 294.

[56] Juul, p. 64.

Generators

Despite the attempts to hold windmill speed constant at the value that will produce the desired frequency, some small variation is inevitable due to the wide range of wind speed variations. Fortunately, if the power network is very large compared to the wind generating station, the network itself will force the generator to run at a speed synchronized to the network frequency. A synchronous generator coupled to a windmill and running in parallel with a network can run at only one speed, the synchronous speed. However a control mechanism, such as pitch control, is necessary to hold the input power fairly constant.

Another type of generator is an induction machine. It becomes a generator when run above synchronous speed. The speed of the windmill is constrained by the power network frequency, however. The generator runs at slip angles above synchronous speed determined by the network frequency. A speed control is needed, but with less stringent requirements than for the synchronous generator.[57]

Variable Speed-Constant Frequency

When a windmill blade system operates at a constant pitch, the speed of the windmill will vary with the speed of the wind, and the power will vary with the cube of the wind speed. The pitch angle can then be set to produce the

[57] Jaya Devaiah, 544.

maximum power coefficient obtainable from that blade system and the power coefficient will remain constant for all wind speeds. This allows the windmill to harness a much greater amount of power than if it were run at a constant speed. In addition, the mechanisms for providing pitch adjustment and control are eliminated. These advantages are offset by the varying angular velocity of the windmill and the accompanying variable frequency.

To solve this problem, a device for converting variable frequency to constant frequency must be used. Several schemes are available for carrying out this conversion, but they are generally more complicated than constant speed systems.

AC-DC-AC Conversion System

An AC generator with a DC field excitation coupled to a varying speed windmill will produce varying frequency. A rectifier applied to this current will convert it to direct current. Next an inverter is used to convert the electricity back to alternating current, but at the desired frequency, as illustrated in Figure 12. The technology to do this is established and in use in high voltage DC transmission. The equipment for this conversion is expensive though, and this method usually only pays off if long distance transmission is involved.[58]

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[58] Jaya Devaiah, 545.

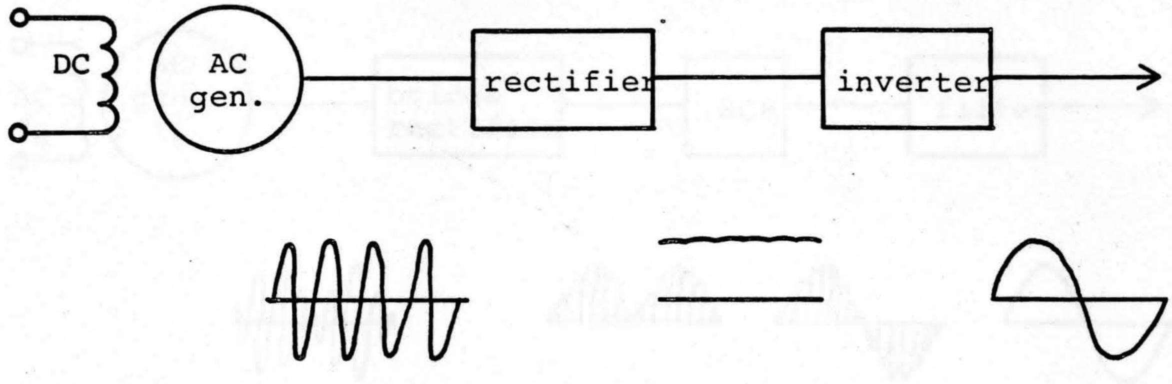

Fig. 12-- Schematic diagram of AC-DC-AC conversion system.

Power Modulation and Demodulation

If the field of an AC generator is excited by the alternating current of a power network then the output is an amplitude modulated wave of the form:

$$V = A(\cos 2\pi f_e t)\ (\cos 2\pi f_r t) \tag{19}$$

where f_e is the frequency of excitation, in this case the frequency of the power network, and f_r is the rotational frequency of the generator. This wave is shown in Figure 13 and it can be described as a sine wave curve with a frequency of f_r and an amplitude that varies to fit in the modulation envelope that has a frequency of f_e. To derive f_e output demands that f_r be many times greater than f_e meaning the generator has to run at a very high speed. This modulated signal is demodulated by a bridge rectifier and a silicone controlled rectifier, and then filtered to give the desired frequency.[59]

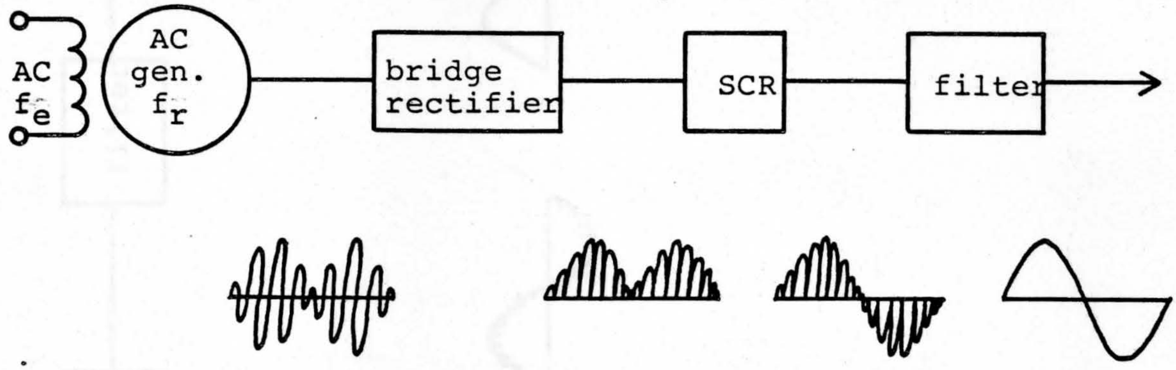

Fig. 13-- Schematic diagram of a simple modulation and demodulation scheme.

ARH Scheme

A generation scheme similar to the single phase modulation and demodulation system shown in Figure 13 has been proposed by Allison, Ramakumar, and Hughs (ARH) of Oklahoma State University. This scheme is also referred to as a frequency down conversion system. Instead of using a single phase generator, a three phase generator, excited by the power network is used. This produces 3 amplitude modulated waves. The modulation envelopes of each of these waveforms are exactly in phase, but the high frequency portions are displaced from each other by 120^0. When each wave is passed through its own bridge rectifier the resulting half waves shown in Figure 14 are still out of phase. When the three waves are placed in series, switched by the SCR

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[59]Jaya Devaiah, 546.

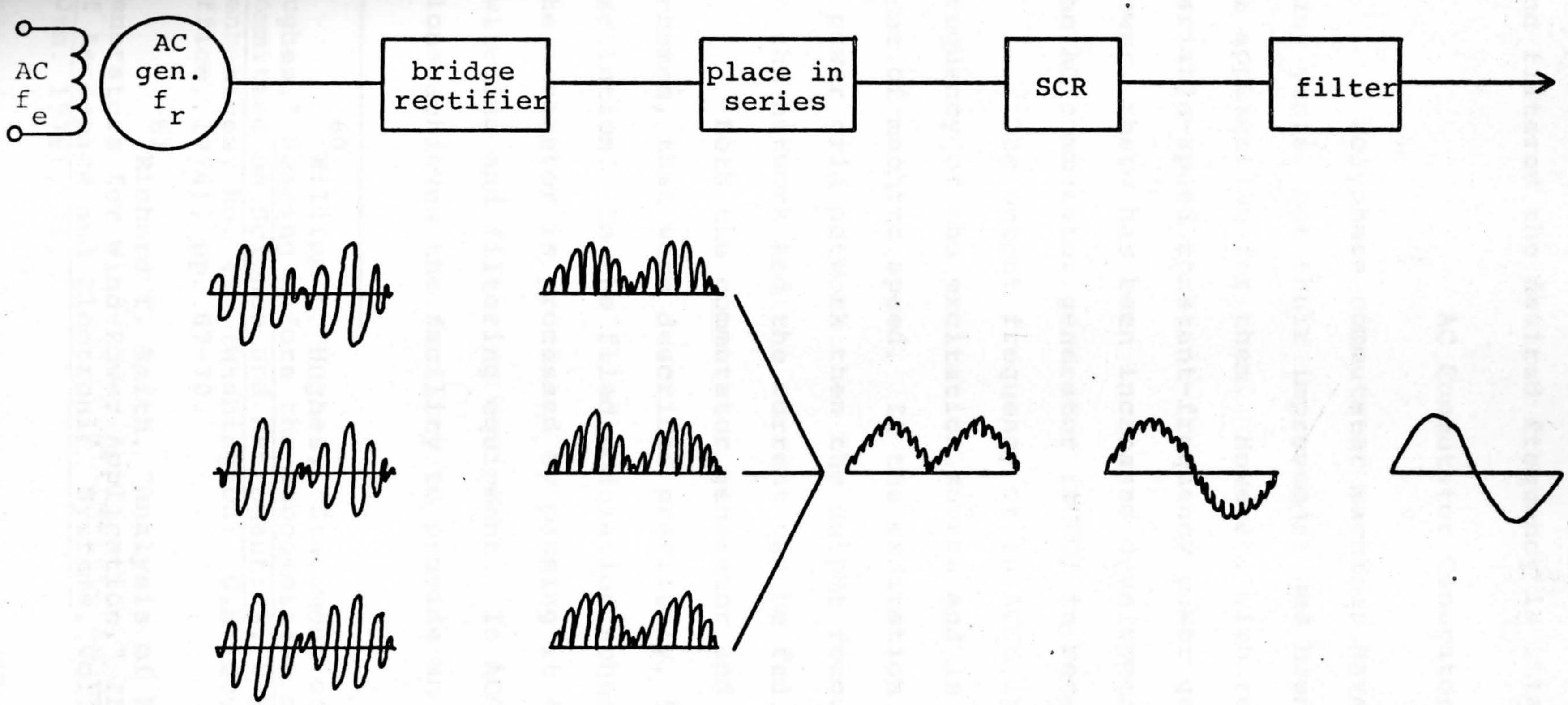

Fig. 14-- ARH scheme of down conversion and filtering.

and filtered the desired frequency is obtained.[60]

AC Commutator Generator

Polyphase commutator machines have been in use for many years, but their improvement has been slow due to lack of application for them. However, with renewed interest in variable-speed constant-frequency power generation by wind power, there has been increased development time spent on the AC commutator generator (ACCG) in recent years.[61]

The output frequency of an ACCG is the same as the frequency of the excitation source and is completely independent of machine speed. If the excitation is derived from a power grid network then the output frequency will be matched to the network and the current can be fed into it.

Both the commutator generator and the field modulation schemes, that were described previously, take line frequency excitation. In the filed modulation schemes the output of the generator is processed by passing it through elaborate switching and filtering equipment. In ACCG, a commutator alone achieves the facility to provide an output frequency

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[60] William L. Hughes, "Statement of Prof. William L. Hughes," Hearing before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, No. 49, (Washington: U.S. Government Printing Office, 1974), pp. 67-70.

[61] Richard T. Smith, "Analysis of Polyphase Commutator Generators for Wind-Power Application," IEEE Transactions of Aerospace and Electronic Systems, Vol. AES-12, No. 1, (Jan. 1976), 39.

equal to the excitation.[62] Since the rest of the systems are almost the same, the difference between the two is in the commutator versus the solid state processors.[63]

The commutator is rugged, cheap and reliable. It has the benefits of decades of technical progress behind it, since a commutator is used in all rotating electric machines. The construction of an ACCG is similar to that of a DC generator and the costs of these two devices are comparable. The only limitation to ACCG is commutation difficulties in very large machines, therefore sizes are limited to 225 kilowatts per pole. However, a generator with four poles can provide a capacity of 900 kilowatts which is in the right range for most wind generating systems. If larger capacities are needed, two or more generators could be run in parallel. The size limitation of ACCG does not present a great handicap for wind generating systems.[64]

When an ACCG is fully compensated it has the same terminal characteristics as a DC generator.[65] Compensating windings are windings placed in slots in the face of the field poles to help produce a smoother output and to improve commu-

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[62] The commutator of an electric machine is mounted on the rotating shaft and provides a contact surface for the brushes to rub against, so electric current can be passed to or from the rotating coil windings through the stationary brushes, brush holders and connecting wires.

[63] Jaya Devaiah, 548.

[64] Jaya Devaiah, 549.

[65] Jaya Devaiah, 548.

tation.

Matching Power Characteristics of Wind Windmill, Generator, and Load

The overall efficiency of a wind generating system involves not only the individual characteristics of the blade system, generator and storage device, if used, but also their relationship to one another.[66] If the windmill is designed to operate at a constant tip speed ratio the input power will then be proportional to the instantaneous power in the wind. The reason for allowing the tip speed ratio to remain constant is so that the system can capitalize on the greater power in the faster wind.

Since the power in the wind varies as the cube of its velocity, the generator must be able to generate electricity in the approximate relationship of power to angular velocity cubed. If it can't, the advantage of maintaining a constant tip speed ratio is diminished greatly.

Figure 15 shows the power characteristics for a windmill operating with a fixed tip speed ratio at different values of wind speed. In order to operate at high efficiency

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[66] J. G. Walker, "Utilization of Random Power with Particular Reference to Small-Scale Wind Power Plants," Proceedings of The United Nations Conference on New Sources of Energy-Wind Power, Rome, Aug. 21-31, 1961, vol. 7, (New York: United Nations, 1964), p. 371.

the generator output should follow the "Maximum power line" shown in the figure. However, the generator input curve should not approach the "maximum power line" too closely, in order to avoid the possibility of stalling.[67]

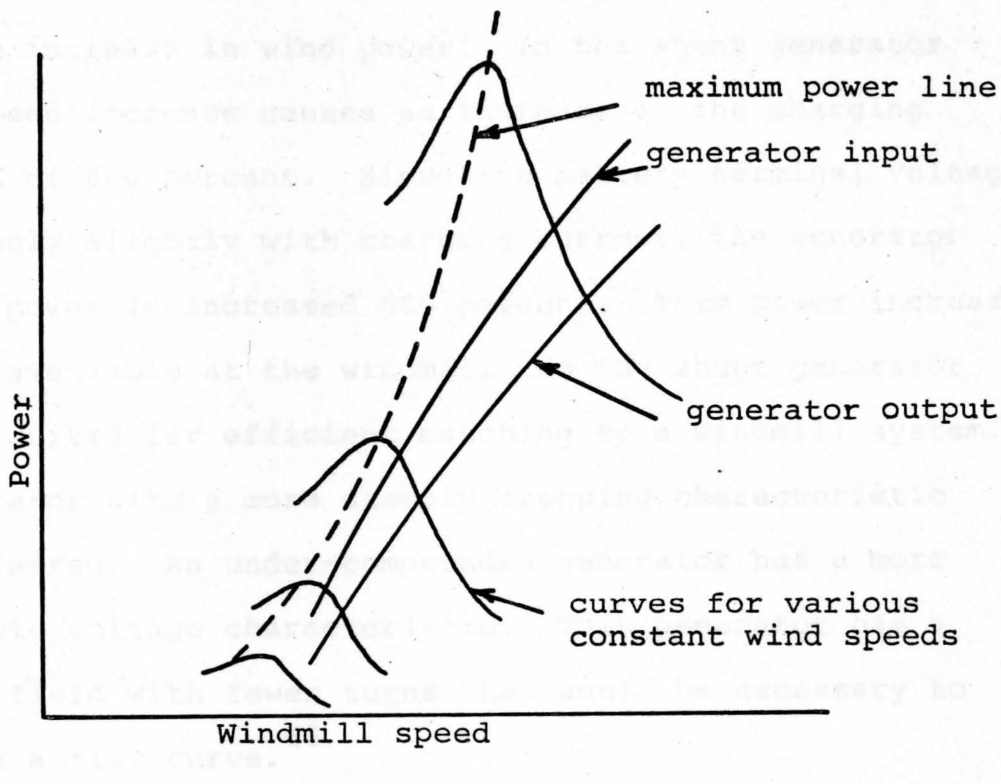

Fig. 15-- Graph of power vs speed.

The voltage characteristics of a generator are determined by the method of connecting the field coils. Series machines have the field connected in series with the armature; shunt machines have the field connected in parallel to the armature; and compound machines have the field connected to the armature in both series and parallel. The graph of the voltage characteristics shows voltage versus current for a family of curves as shown in Figure 16

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[67]Walker, p. 370.

for a shunt-connected generator. The battery characteristics for the fully charged and half charged conditions are also shown. At the half charged condition, a 25 percent increase in generator speed is equivalent to a 95 percent increase in wind power. In the shunt generator this speed increase causes an increase in the charging current of 600 percent. Since the battery terminal voltage rises only slightly with charging current, the generator output power is increased 600 percent. This power increase is not available at the windmill, so the shunt generator is not suited for efficient matching to a windmill system. A generator with a more steeply drooping characteristic is preferred. An under-compounded generator has a more desirable voltage characteristic. This generator has a series field with fewer turns than would be necessary to produce a flat curve.[68]

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[68]Walker, p. 371.

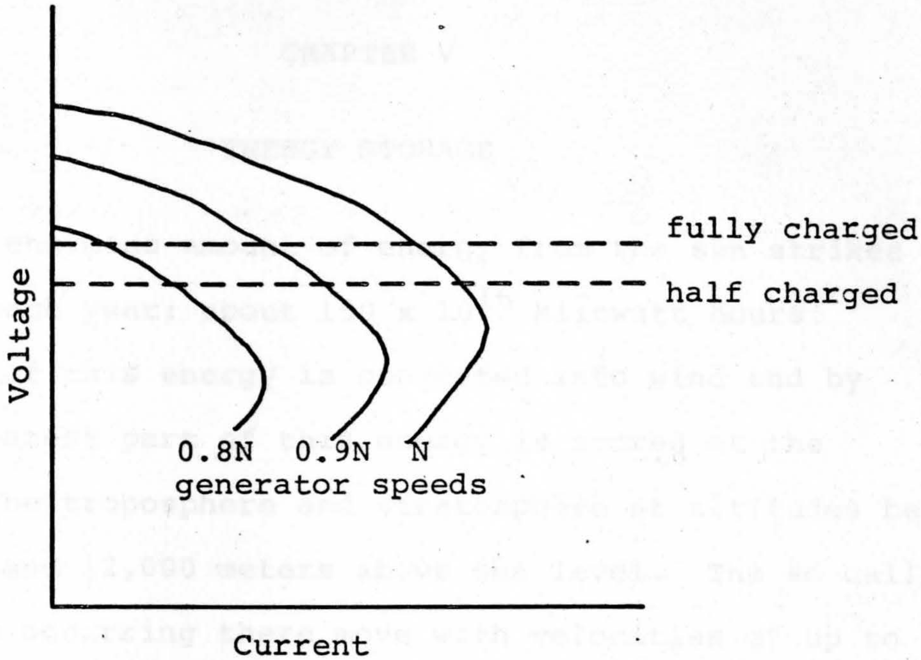

Fig. 16-- Graph of voltage vs. current for a shunt generator.

CHAPTER V

ENERGY STORAGE

An enormous amount of energy from the sun strikes the earth each year; about 150 x 10^{16} kilowatt hours. About 1.7% of this energy is converted into wind and by far the greatest part of this energy is stored at the border of the troposphere and stratosphere at altitudes between 9000 and 12,000 meters above sea level. The so called jet streams occurring there move with velocities of up to 320 kilometers per hour.[69]

A great deal of wind does occur at ground level, however, and it is available for whatever use mankind can devise. Unlike fossil fuel reserves, the wind is an inexhaustable supply of energy. Its quantity at any particular site is predictable over the span of a year based on statistics and past data. The wind is free, not subject to detrimental price fluctuations or foreign influence. The problems and cost of transporting fuel is eliminated and there are minimal enviromental effects. The technology is available today to produce substantial amounts of electricity from wind systems.

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[69] Hans Thirring, Energy for Man, (Bloomington: Indiana University Press, 1958), pp. 262, 279.

Despite the basic advantages of wind power, the nature of the wind within a short interval of time is very uncertain.[70] When wind-generated power is the sole source of power some form of storage is required. Some of the more common forms of energy storage are:

1. Batteries that store energy in chemical form which can be easily converted to direct current electricity.
2. Compressed air which can be stored and used when needed.
3. Massive flywheels made of high strength materials are currently receiving some interest as energy storers.
4. High pressure electrolysis of water which produces hydrogen (H_2) and oxygen (O_2). The hydrogen can be used directly as a fuel or it can be combined with the oxygen and organic materials to manufacture conventional fuels. Another possibility here is the use of a fuel cell to convert the chemical energy of hydrogen and oxygen directly into electricty through a reverse electrolysis process.
5. Magnetic fields for storing energy have also been found to be theoretically possible.[71]

The most basic problem in energy storage is concerned with the energy density that can be achieved. Energy

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[70] Le Boff, p. 362.

[71] Hughes, "Basic Information on The Economic Generation of Energy," pp. 8-9.

density can be defined two ways, either the amount of energy per unit volume or the energy per unit mass. Secondly it is desirable to avoid the use of expendable materials in the process of storing energy. It is also desirable that no particular geographic characteristics be an absolute requirement for the success of an energy storage method.[72]

Battery

The electric storage battery has a long record of reliable service, and its efficiency is relatively high, usually over 85%[73] However, batteries are large, heavy and expensive.

Many designs of batteries have appeared since the lead acid battery became widely used. Many more reactions involving the gain or loss of electrons initially appeared attractive for use in power-producing electrochemical cells. Actually not all these proved capable of supporting appreciable currents at practical voltages in batteries.[74]

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[72]W. L. Hughes, C. M. Summers, and H. J. Allison, "An Energy System for the Future," IEEE Transactions on Industrial Electronics, May 1963, 1-2.

[73]George Wood Vinal, Storage Batteries, (New York: John Wiley & Sons, Inc., 1930) pp. 320-322.

[74]Ernest B. Yeager and Eugene P. Schwartz, The Primary Battery, Vol. I, ed. by George W. Heise and N. Corey Cahoon, (New York: John Wiley & Sons, Inc., 1971) p. 59.

Some of the successful battery designs are the zinc-silver oxide cell, the cadium-nickel oxide cell, the nickel-iron cell, and the lead acid cell.[75]

The capacity of a storage battery can be expressed in two ways, either in ampere-hours or in watt-hours. The ampere-hour capacity is a measure of the quantity of electricity which the battery is able to deliver. The watt-hour capacity is a measure of the energy or ability to do work. The watt-hour capacity is related to the ampere-hour capacity by multiplying the ampere-hour capacity by the average value of the voltage during the discharge period. An approximation of the watt-hour capacity can be calculated by finding the product of the ampere-hour capacity, the number of cells in the battery and the normal voltage of the cells in that type of battery. For instance the normal voltage of a lead-acid type of battery is 2 volts per cell and for a nickel-iron type it is 1.2 volts per cell.

The ampere-hour capacity is the usual way batteries are classified. It is a simpler measurement to make, and in nearly all applications of storage batteries, the current requirement is an important and controlling factor. This is because the output of electrical devices is proportional to the current.[76]

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[75] Raymond Jasinski, High-Energy Batteries, (New York: Plenum Press, 1967) p. 47.

[76] Vinal, p. 183.

When stating the capacity of a battery it is necessary to include the rate at which it is being discharged. The time rating tells the capacity that can be delivered within a specified time. Current rating gives the capacity that can be obtained at some particular current. The time rating is preferred to the current rating because the time rating makes the capacities of different sizes of batteries comparable, whereas a current rating irrespective of the size of the battery imposes a less severe tax on the larger sizes and their capacity appears more than proportionately greater. The current is easily found by dividing the ampere-hour capacity by the time rating.[77]

As a battery discharges, the voltage at the terminals falls gradually from its open circuit value until the end of the discharge is approached, when it begins to fall much more rapidly. Only a small percentage of the total capacity can be obtained by continuing to discharge beyond this point. On a plot of the voltage throughout the period of discharge, the point where the curve begins its rapid fall is known as the knee of the curve. It is not economical to discharge the battery beyond the knee or proper end point. The discharge rate determines the amount of the battery capacity that is discharged before reaching the knee. Less capacity is discharged as the current increases, which is another

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[77] Vinal, p. 184.

way of saying, as the time rating is decreased.[78]

The principle factors that affect the storage capacity are: the amount of material within the cell, the thickness of the plates, the rate of the discharge, the temperature, the concentration of the electrolyte, the porosity of the plates, the design of the plates, and the previous history of the plates.[79]

Briefly expanding on each of these factors, the amount of electricity, or the number of valance electrons available to flow, is directly related to the amount of material within the cell. A theoretical amount of material corresponding to each ampere-hour of capacity can be calculated by the use of Faraday's law.[80] For every 96,500 coulombs, or ampere-seconds, one equivalent of each reacting material is transformed. By dividing the amount of one equivalent of each material by the charge, corrected to ampere-hours, the amount of material transformed during the passing of one ampere-hour is found. For example, in the lead-acid cell the ratio of one atom of lead, one molecule of lead peroxide, and two molecules of sulphuric acid react to produce the electric charge. The atomic weight of lead is 207.2 and the valance is two, so one equivalent weight

[78]Vinal, p. 185.

[79]Vinal, p. 186.

[80]A more complete explanation of Faraday's law is presented later on page 78.

of lead is 103.6 grams. Now 96,500 coulombs is equal to 26.80 ampere-hours, so 103.6 grams divided by 26.80 ampere-hours yields 3.866 grams of lead must be transformed into lead sulphate to produce one ampere-hour of electricity. Similarly, the molecular weight of lead peroxide is 239.2 and the valance is two; so the weight of one equivalent, 119.6 grams, divided by 26.80 ampere-hours shows that 4.463 grams of lead peroxide must also be transformed. The molecular weight of sulphuric acid is 98.08, the valance is two, and two molecules must react for every one atom of lead. Therefore, there are 98.08 grams of acid reacting for each equivalent of lead. This amounts to 3.660 grams per ampere-hour.[81]

The foregoing figures showing the relation of lead, lead peroxide, and sulphuric acid consumed per ampere-hour are based entirely upon theoretical considerations. The practical amounts of the active materials required are considerably greater than those calculated from theory. The lead sulphate which is formed during the process of discharge is a nonconductor and increases the resistance of the active material. The lead sulphate also blocks the pores of the active material which hinders the diffusion of the electrolyte. Thirdly, the electrolyte's resistance increases as the content changes from acid to water. A fourth reason involves the limited contact between the active material

[81]Vinal, p. 187.

and the electrolyte compared to the total amount of active material.[82]

The capacity of a storage cell increases with the thickness of the active material of the plates, assuming the plates have sufficient porosity for the electrolyte to reach the inner recesses. The rate of discharge, however, determines how much of the inner portion of the plate is utilized. A fast discharge does not allow enough time for the electrolyte to diffuse into the pores of the plate and the material that is formed during the reaction can clog the pores of the plate. At low rates of discharge, on the other hand, almost any depth of the active material can be effective.[83]

Even though thick plates have a greater capacity per plate than thin plates, the capacity of equal sized cells is greater for the cell that contains thinner and a greater number of plates. This is particularly true at high discharge rates.[84]

For any specified amount of material and plate thickness the area of the plate is determined. Therefore, the area is not an independent factor in determining cell capacity, but it is easily measured and is often used when capacity is being determined.[85]

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[82] Vinal, p. 188.

[83] Vinal, p. 193.

[84] Vinal, p. 189.

[85] Vinal, p. 195.

The effect of the rate of discharge on cell capacity has been discussed previously. Summarizing, the capacity is decreased as the rate increases due to the closing of the pores by the resulting compounds; the limited time available for diffusion of the electrolyte; and, the loss of voltage because of internal resistance of the cell.[86]

The temperature affects the capacity in at least three ways. The resistance of the electrolyte is decreased as the temperature increases. Second, the voltage is raised as the temperature increases. The third way is the rate of diffusion of the electrolyte into the pores of the plate increases as the temperature increases.[87]

The concentration of the electrolyte in the pores of the plates is vital in determining the voltage and the capacity. If the electrolyte in the pores is depleted the voltage will fall and the cell will become exhausted. The capacity is affect by the concentration because it affects the potential of the plates, the resistance of electric current through the electrolyte, and the viscosity of the electrolyte which affects the rate of diffusion. In addition, the rate of diffusion is also determined by the difference in concentration of the electrolyte in the pores and outside.[88]

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[86]Vinal, p. 196.

[87]Vinal, p. 202.

[88]Vinal, p. 204

The importance of the pores to giving the electrolyte access to the active material has been indicated in the discussion of the other factors. The individual pores are molecular in size but the aggregrate porosity of a plate can be in the range of 50% of the volume. The porosity is defined by taking one minus the ratio of the apparent density of the material to the real density. Multiplying by 100 gives the percentage of porosity.

The material of the plate can determine the porosity, but the state of charge also causes the porosity to change. The product that is formed by the discharge of the cells is usually less dense than the original material. It therefore occupies more space than the active materials, yet the apparent volume of the plate does not change. The expansion is taken up by the pores, which decreases the porosity as the cell is discharged.[89]

Battery plates increase in capacity slightly after the first few discharge-charge cycles. Then the capacity remains fairly constant and then begins to fall gradually. When the capacity falls to 80% of their initial capacity the plates are considered to be useless. Thin plates usually loose their capacity sooner than thick ones. The loss of capacity stems from decreased porosity or shrinkage in the negative plate and from loosening of the active

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[89] Vinal, p. 204.

material on the positive plate.[90]

Since its development, the storage battery has played a big role in energy storage. Indications are that it will be relied on to a greater degree in the future due to its reliability and due to new and anticipated improvements that will minimize its disadvantages.

Compressed Air

Unlike many methods of energy storage that are theoretically possible, but are still in the infancy of practical large scale application, the compression of air represents a very old technology. Air is routinely compressed to very high pressures in industry. Generally, the only limitation is the number of compression stages through which the air is processed. Cooling is usually employed to limit the temperature rise in the compression stages but no other particular problems are encountered in the compression of air.

The energy stored in compressed air can be used by allowing the air to expand to normal pressure through an appropriate pneumatic device. The amount of energy available from a gas stored at pressure p_2 and volume v_2 by isentropic expansion to pressure p_1 is given by

$$E = p_1 v_2 \left(\frac{k}{k-1}\right)\left(\frac{p_2}{p_1}\right)^{\frac{1}{k}} \left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} -1\right] \qquad (20)$$

[90]Vinal, p. 213.

where k is the ratio of specific heats for constant pressure and constant volume, c_p/c_v. At 27 Celsius k = 1.4 for air.

The use of compressed air for storing large quantities of energy requires the use of very high pressures, very large volumes, or both. The technology that has been developed by the natural gas industry for storing large quantities of gas in underground geologic reservoirs can be easily adapted to storing compressed air.[91]

The conversion of compressed air to electricity can be accomplished in at least two ways. One method is for the expanding air to drive an air, or fuelless, turbine. The other is to inject the compressed air into a gas, or fueled, turbine to eliminate the usual compression stages.

A modern gas turbine consists of an air compressor, a fuel chamber for heating the compressed air and a turbine in which adiabatic expansion of the hot compressed air converts kinetic energy to rotational mechanical energy. About 70% of the power produced by a gas turbine is consumed by the air compressor. By using compressed air from another source the compression stage is omitted and the available energy output is increased approximately 300%. If a given amount of energy is required from the turbine the turbine system can be reduced to 1/3 that which would

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[91]Robert K. Swanson, Craig C. Johnson, and Richard T. Smith, Wind Power Development in the United States, Southwest Research Institute Special Report, Feb. 15, 1974, pp. 2-4.

usually be required and the fuel energy that was used for the compression stage is not consumed.[92]

Flywheel

When the energy in the wind is converted to mechanical energy by the windmill, the energy can be stored in the form of rotating mechanical energy in a flywheel. This storage method is different than others because the energy is not converted into another form for the purpose of storage. Furthermore, when electricity is needed no energy conversion is required prior to input into the generator. This arrangement with its minimum number of conversions results in an extremely efficient storage system: about 95% efficient.[93]

The kinetic energy stored in a flywheel is expressed by

$$E_K = \tfrac{1}{2} I_m \omega^2 \tag{21}$$

where I_m is the mass moment of inertia of the rotating member and ω is the angular velocity in radians per second. Energy is received or given up by a change in velocity as shown here.

$$\Delta E_K = E_{K_1} - E_{K_2} = \tfrac{1}{2} I_m \omega_1^2 - \tfrac{1}{2} I_m \omega_2^2 = \tfrac{1}{2} I_m (\omega_1^2 - \omega_2^2). \tag{22}$$

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[92]Swanson, pp. 6-8

[93]Peter Clegg, New Low-Cost Sources of Energy for the Home, (Charlotte, Vt.: Garden Way Publishing, 1975) p. 93.

Usual practice is to keep the variation of flywheel speed within certain limits determined by the class of service in which the flywheel is employed. The ratio of the total variation in speed to the normal speed is called the coefficient of fluctuation, k, and is represented by

$$k = \frac{\omega_1 - \omega_2}{\omega_1} \qquad (23)$$

By solving equation (23) for $_2$ and substituting into equation (22) the following is obtained

$$\Delta E_k = \tfrac{1}{2} I_m \omega_1^2 (2k-k^2) = E_{k_1} (2k-k^2)$$

Rearranging this equation will give an expression for the portion of the total energy stored in the flywheel that can be released to do useful work.

$$\frac{E_k}{E_{k_1}} = 2k-k^2 \qquad (24)$$

Most sources list the greatest coefficient of fluctuation for a flywheel application to be for a punching or shearing machine and list the value to be 0.2. Flywheels that drive alternating current electric machines have a usual range for this coefficient of 0.0003 to 0.003.[94] If $2k-k^2$ is differentiated with respect to k and set equal to zero the value of k corresponding to the greatest value of $2k-k_2$ is found to be 1.0. Since the coefficient of fluctuation will always be less than 1.0, as k decreased so

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[94] P.H. Hyland and J. B. Kommers, Machine Design, (New York: McGraw Hill Book Co. Inc., 1929), pp. 472-474.

will $2k-k^2$ and so also will E_k/E_{k1}. This means that the smaller the value of k, the greater the energy storage capacity it is necessary to provide in the flywheel in order to extract a given amount of energy.

Assume that a generator is used that will work efficiently over a very wide range of speeds, and also that means are provided to adjust the varying frequency and voltage output to a constant value. The coefficient of fluctuation could then be very large to allow a greater portion of the stored energy to be extracted, and thereby reducing the storage capacity of the flywheel.

The energy stored in a flywheel can be increased by increasing the normal angular velocity, increasing the radius, or increasing the mass either by using a larger flywheel cross section or using a denser material. Material density is not easy to adjust because other factors, like cost and strength, determine what the flywheel material will be. The size of the flywheel, both radius and cross sectional area, determines the weight and cost of the flywheel. While larger flywheels are an acceptable approach, it is desirable from a cost standpoint to make the flywheel as small as possible and run it at higher rotating speeds.[95]

The general expression for the centrifugal force created in a mass is

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[95] Omer W. Blodgett, Design of Weldments, (Cleveland: James F. Lincoln Arc Welding Foundation, 1963), p. 5.1-1.

$$F_c = \frac{mv^2}{r} = mr\omega^2. \qquad (25)$$

If there are no initial stresses such as a press fit onto a shaft, and neglecting the stresses caused by the weight of the flywheel, the only stress in the flywheel is caused by the centrifugal force. Therefore the stress in the flywheel increases with the square of the speed. In order to keep flywheel size and cost down high strength materials are needed to safely operate at high speeds.[96]

Electrolysis of Water

When an electric current is passed through a liquid, chemical changes take place at the electrodes. If the liquid is water, the water is decomposed into its constituent elements, hydrogen gas (H_2) and oxygen gas (O_2). This process to decompose compounds by electric energy is electrolysis.

Faraday observed this phenomenon and developed Faraday's laws of electrolysis. The weight of an element formed at an electrode is directly proportional to the amount of electricity passed through the liquid. Also, the weight of the element formed is directly proportional to the atomic weight of the element divided by a small whole number, eg. 1,2,3, etc.[97]

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[96] J. B. Hartman, V. L. Maleev, and M. J. Siegel, Mechanical Design of Machines, (Scranton, PA.: International Textbook Co., 1965), p. 133.

[97] Robert A. Plane and Michell J. Sienko, Chemistry, (New York: McGraw Hill Book Co. Inc., 1961), p. 33.

The electric field pushes electrons in the wires toward one electrode which assumes a negative charge and draws them away from the other which assumes a positive charge. At the negative electrode, or cathode, a reduction process occurs in which some ions or molecules accept electrons. At the positive electrode, or anode, electrons are released by an ion or molecule to the electrode. This is an oxidation process.

To keep the process continuing positive ions, called cations, have to keep moving toward the cathode. Simultaneously, negative ions must move to the anode. Negative ions are called anions.[98]

Pure water is a very poor conductor of electricity. Many water solutions are good conductors, such as dilute sulfuric acid, aqueous sodium sulfate, aqueous sodium hydroxide and aqueous potassium hydroxide.[99]

Each molecule of water contains two atoms of hydrogen, atomic number 1, and one atom of oxygen, atomic number 16; H_2O. If enough electricity flows to produce 1 gram of hydrogen (1 gram-atom) at one electrode then 8 grams of oxygen (½ gram-atom) is produced at the other.[100] The volume of hydrogen produced is twice the volume of oxygen in accordance with Avogadro's Law which states equal volumes of

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[98]Plane, p. 279.

[99]John C. Hogg, et al, Chemistry A Modern Approach, (Princeton: D. Van Nostrand Co. Inc., 1963), p. 113.

[100]Plane, p. 34.

two gases under the same condition of pressure and temperature contain the same number of molecules.[101]

The net reaction for electrolysis of water is

$$2\ H_2O \xrightarrow{\text{electrolysis}} 2H_2\ (g) + O_2\ (g). \qquad (26)$$

For some solutions of water the half-reaction at the cathode is

$$e^- + H_2O \rightarrow \tfrac{1}{2}H_2\ (g) + OH^- \qquad (27)$$

which is expressed in electrons, molecules and ions. This reaction can also be read in terms of gram-molecules and moles if the electricity is expressed in faradays. Specifically, the cathode half-reaction can be read: one faraday of electricity reacts with one gram-molecule of water (18.016g) to form one half gram-molecule of hydrogen gas (1.008g) plus one mole of hydroxide ions (17.008g). A faraday of electricity is defined as the transfer of an Avogadro's number of electrons and is equal to 96 500 coulumbs of charge.[102]

One coulumb is equivalent to one ampere second. Since it is electric current which determines the rate of electrolysis, the power supplied by the windmill generator would be best utilized if it were low voltage, high current electricity.

Several reactions take place during electrolyis of water to finally give the net reaction. Different solutions

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[101]Hogg, p. 139.

[102]Plane, p. 285.

of water electrolyte have different reactions. Aqueous sodium sulfate (Na_2SO_4) solution contains sodium ions (Na^+), sulfate ions (SO_4^{--}) and water (H_20), and it is essentially neutral. The cathode reaction is

$$2e^- + 2H_20 \longrightarrow H_2(g) + 2OH^-, \qquad (28)$$

and the anode reaction is

$$2H_20 \longrightarrow 0_2(g) + 4H^+ + 4e^-. \qquad (29)$$

After the reaction has proceeded for awhile the solution in the vicinity of the cathode tends to be basic because of the OH^- and the solution near the anode tends to be acidic from the H^+.

The overall cell reaction takes place by mixing the solutions. The equation is written by doubling the cathode reaction and adding it to the anode reaction.

$$6H_20 \xrightarrow{\text{electrolysis}} 2H_2(g) + 0_2(g) + 4H^+ + 4HO^- \qquad (30)$$

The four electrons cancel. The neutralization reaction is

$$4H^+ + 4OH^- \longrightarrow 4H_20 \qquad (31)$$

and when added to the overall cell reaction gives the net reaction;

$$2H_20 \xrightarrow{\text{electrolysis}} 2H_2(g) + 0_2(g). \qquad (32)$$

In this electrolysis, only water disappears. The Na^+ and $S0_4^{--}$ initially present are also present at the conclusion of the electrolysis. Because of the requirements of electrical neutrality, some kind of electrolytic solute must be present. Positive ions must be available to move into the cathode region to counterbalance the charge of the

OH^- produced. Negative ions must be available to move to the anode to counterbalance the H^+ produced.[103]

The electrolysis of dilute sulfuric acid (H_2SO_4) has three acceptable versions of reaction to electrolysis. The first explanation starts with the dissociation in the water solution of the sulfuric acid to give hydrogen ions and sulfate ions:

$$2H_2SO_4 \longrightarrow 4H^+ + 2SO_4^{--}. \quad (33)$$

The cathode reaction is

$$4e^- + 4H^+ \longrightarrow 2H_2(g) \quad (34)$$

and the anode reaction is

$$2SO_4^{--} \longrightarrow 2SO_4 + 4e^-. \quad (35)$$

The sulfate groups (SO_4) are unstable and react at once with water to release oxygen:

$$2SO_4 + 2H_2O \longrightarrow 4H^+ + O_2(g) + 2SO_4^{--}. \quad (36)$$

The net effect is:

$$2H_2O \xrightarrow{\text{electrolysis}} 2H_2(g) + O_2(g). \quad (37)$$

The second explanation for the electrolysis of dilute sulfuric acid is based on the slight ionization of water.

$$4H_2O \longrightarrow 4H^+ + 4\ OH^- \quad (38)$$

There are now two kinds of negative ions (OH^- and SO_4^{--}) in solution. The sulfate ion is more stable than the hydroxide

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[103]Plane, pp. 282-283.

ion so the hydroxide ions are discharged at the anode.

$$4\ OH^- \longrightarrow O_2(g) + 2H_2O + 4e^- \qquad (39)$$

As hydroxide ions are discharged the water equilibrium is disturbed and according to LeChalelier's principle water will continuously ionize to restore the equilibrium. Thus we can think of water rather than acid as the source of the hydrogen ions discharged at the cathode.

$$4e^- + 4H^+ \longrightarrow 2H_2(g) \qquad (40)$$

The net reaction is:

$$2H_2O \xrightarrow{\text{electrolysis}} 2H_2(g) + O_2(g). \qquad (41)$$

The third explanation says the cathode supplies electrons to nearby water molecules.

$$4e^- + 4H_2O \longrightarrow 2H_2(g) + 4\ OH^- \qquad (42)$$

The anode removes electrons from water molecules.

$$2H_2O \longrightarrow O_2(g) + 4H^+ + 4e^- \qquad (43)$$

The reactions can be added to give

$$6H_2O \longrightarrow 2H_2(g) + O_2(g) + 4H^+ + 4\ OH^-. \qquad (44)$$

The hydrogen and hydroxide ions combine to form water and the net reaction is:

$$2H_2O \xrightarrow{\text{electrolysis}} 2H_2(g) + O_2(g).\text{[104]} \qquad (45)$$

The electrolysis of aqueous sodium hydroxide (NaOH) also yields hydrogen and oxygen gas. Sodium hydroxide is

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[104] Hogg, pp. 319-321.

completely ionized in aqueous solution.

$NaOH \rightarrow Na^+ + OH^-$ (46)

The water ion equilibrium is:

$4H_2O \longrightarrow 4H^+ + 4OH^-.$ (47)

There are two kinds of cations, Na^+ and H^+. Na^+ is more stable than H^+ and as a result H^+ is more readily discharged at the cathode.

$4e^- + 4H^+ \longrightarrow 2H_2(g).$ (48)

The anode reaction is:

$4\ OH^- \longrightarrow O_2(g) + 2H_2O + 4e^-,$ (49)

and the net reaction is again

$2H_2O \xrightarrow{\text{electrolysis}} 2H_2(g) + O_2(g).$[105] (50)

Aqueous potassium hydroxide reacts similarly to electrolysis as aqueous sodium hydroxide and the net reaction is the same.

In some cases the electrodes themselves may take part in the electrolysis reaction. If the electrode material is reactive, such as copper, it must be considered as a possible reactant. Inert metals such as platinum will not react.[106]

Electrolysis at extremely high efficiency can be done at pressures as high as 200 or 300 atmospheres. The hydrogen is stored in high pressure tanks and the oxygen can

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[105] Hogg, p. 32.

[106] Plane, p. 284.

either be released to the atmosphere or stored and used in future energy conversion reactions. Since oxygen is readily available from the atmosphere the economics of storing oxygen versus pumping and filtering air will largely determine which route to take. Automatic controls can be used to accelerate or decelerate the electrolysis process based on the pressure in the hydrogen storage tank. The hydrogen in the tank is released through a pressure reducer to several possible energy conversion devices. The amount released would need to be controlled by the load demand. The resulting water by product from the conversion can be recirculated into the pressure electrolysis system.[107]

There are several possible mechanisms for releasing the chemical energy in hydrogen. A hydrogen burner can produce heat by burning the hydrogen just as other gaseous fuels are burned. Hydrogen has by far the highest heat value per mass of any fuel. When one gram of hydrogen is completely burned, 142 kilojoules of heat are released. Methane has a heat value of 55 kilojoules per gram and ethane and propane have values of 51 kJ/g.[108] Hydrogen fuel can also be injected into an internal combustion engine designed to operate with such a fuel. Another possibility is to recombine the oxygen and hydrogen in an aphodid burner to produce steam which can be used to drive a steam tur-

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107 Hughes, "An Energy System for the Future", p. 4

108 Hogg, p. 219.

bine.[109]

The most efficient way to convert hydrogen to electricity is the fuel cell. The fuel cell operates on the same principle as the galvanic cell. These two devices represent the most direct method of converting into electrical energy the energy liberated in a reaction between chemical substances. The special feature of the fuel cell is that its chemical reactants are stored outside the cell.

The electrodes in the fuel cell are stable conducting surfaces at which the chemicals react, leaving the electrodes intact but either donating or accepting electrons which then flow in the external circuit. The running time of such a cell is quite unlimited by its physical dimensions since the reacting chemicals may be fed in from a pipeline. The cell can run continuously or at any rate until the electrodes wear out either mechanically or chemically by corrosion.[110]

When hydrogen and oxygen combine to form water the electrons in the outer shells are rearranged and assume a lower energy state, thereby releasing energy. In an electric cell when this chemical reaction takes place a smooth but defined path is laid out for electrons to take passing from one atomic position to another which is a wire conductor

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[109] H. Jack Allison, "A Wind Energy Storage Technique Utilizing a Hydrogen-Oxygen Electrolysis Cell System", A Synopis of Energy Research, 1960-1974, (Stillwater, Oka., Engineering Energy Laboratory, Oklahoma State University, (1974), p. 10-5.

[110] A. B. Hart and G. J. Womack, Fuel Cells Theory and Application, (London: Chapman and Hall Ltd., 1967) p. 1.

through a machine or other electrical load doing useful work.[111]

In the direct conversion of chemical energy of reacting substances into electricity in a chemical cell four conditions must be fulfilled. 1) The cells should be so designed that the active species are transplanted to the reaction sites where electrochemical reactions occur. 2) The reaction should occur rapidly and go to completion; this may require the use of catalysts to reduce the activity energy of the particular reaction. 3) The reaction products should be transported efficiently away from the reaction site, and 4) The electric current which flows when electron transfer takes place during the chemical change reaction should be conducted through an external circuit where useful work may be performed.[112]

The complete cell process may be divided into three stages. In two of these, the reactants must separately be able to exchange their electrons with an electronic conductor. The third is that in which one of the reactants must be able to form charges or ionized species which can move between the electrodes and so carry out the molecular rearrangement which is also necessary in forming the product.

In the case of hydrogen and oxygen, the reaction at

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[111]Hart, pp. 9-10.

[112]Hart, p. 11.

the hydrogen electrode is:

$2H_2 \longrightarrow 4H^+ + 4e^-$. (51)

The H_2 molecule partly donates or shares an electron from each of its atoms to the electrode which then holds the positively charged hydrogen ion in position at its surface by coulombic attraction. Metals do not catalyse this reaction with equal ease. Those which do so readily are platinum, palladium and nickel which are metals that can readily accomodate extra electrons within their atomic structure.

The reaction at the oxygen electrode is:

$4e^- + O_2 + 2H_2O \longrightarrow 4OH^-$. (52)

The hydroxide ion is formed since the charged oxygen atom (O^{--}) is not stable in aqueous solution.

$O^{--} + H_2O \rightarrow 2\ OH^-$ (53)

The metals which form a hydroxide ion and which do not oxidize too readily are gold, silver, platinum and nickel. Nickel does form an oxide coat which acts as an insulator, but can be doped with lithium ions to increase its electronic conductivity.

The electronic transfer is different for an alkaline solution and an acid solution. In an alkaline solution the hydroxide ions from the electrolyte combine with the hydrogen ions at the hydrogen electrode to form water.

$4H^+ + 4\ OH^- \longrightarrow 4\ H_2O$ (54)

The hydroxide ions from the oxygen electrode replace those used in the electronic transfer reaction.

In an acid solution the hydrogen ions from the acid combine with the hydroxide at the oxygen electrode. The hydrogen ions from the hydrogen electrode dispense and maintain neutrality in the solution.

The overall process is the same as in combustion; the reaction of two molecules of hydrogen and one molecule of oxygen form two molecules of water, but with the difference that four equivalents of electrons must move in an external circuit under the chemical pressure of the reaction.[113]

The cell voltage is a measure of the electron pressure to which the chemical reaction gives rise. The pressure, or concentration of the reactants at the electrodes, and the temperature influence the voltage when no current is flowing (open circuit voltage). When the current does flow and the processes begin to occur at appreciable rates the cell voltage falls off.

Refer to open circuit voltage as E (electromotive force of the reaction: 1.23 volts for hydrogen - oxygen at one atmosphere pressure and 298K) and working, or closed, voltage as V. When the fuel cell operates for enough time to convert one mole of hydrogen to water, two faradays of electricity must be generated. Suppose the voltage is V. The work done is [V x 2 x 96 500] volt· coulombs or joules, but if the same change occurs at open circuit, or an infinitesimally small current, then the work is [1.23 x 2 x

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[113]Hart, pp. 12-13.

96 500]J. The difference appears in the cell as heat [2 x 96 500 (1.23 - V)]. The ratio V/1.23, or more generally V/E, is a ratio of the actual to theoretical work and is called the electrochemical efficiency of the cell.

The heat loss, [2 x 96 500 (E-V)] joules per mole of water is a function of the current and may be thought of as being made up of various frictional losses which are associated with electron flow in the chemical reactions and with the flow of ions in the electrolyte, which result in ohmic heating.[114]

Magnetic Fields

Energy can be stored by creating intense magnetic fields inside an electrical coil carrying a very high current. Heat losses resulting from the resistance in the coil would soon outweigh the energy storage capacity unless coils which have no electrical resistance were used. This is possible by using materials that have a zero resistance characteristic at cryogenic temperatures. The problems of holding a large storage system at cryogenic temperatures are not simple, however. Further, if high energy densities are to be achieved, and if at any moment some part of the system becomes nonsuperconducting, all of the energy will be dissipated in a short time. This would constitute an explosive hazard of great magnitude. Another problem that requires

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[114] Hart, pp. 14-16.

attention is the extremely high mechanical stresses on the storage coil. This will require materials with high structural strength at cryogenic temperatures.[115]

The amount of energy that can be stored in a magnetic field can be determined by considering the single loop circuit containing a resistor, R, and an inductor, L, that is shown in Figure 17.

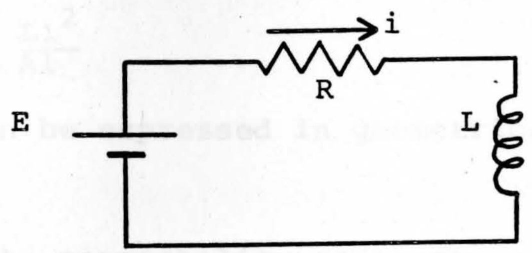

Fig. 17-- Single loop circuit

The differential equation that describes the growth of current in this circuit is:

$$E= iR + L\frac{di}{dt}. \qquad (55)$$

Multiplying by i gives:

$$Ei = i^2R + Li\frac{di}{dt}. \qquad (56)$$

Ei is the rate at which the source of electromotive force delivers energy to the circuit, i^2R is the rate at which energy appears as Joule heat in the resistor, and Li di/dt is the rate at which energy is stored in the magnetic field.

[115]Hughes, "An Energy System for the Future", p. 1-2.

$$\frac{dW}{dt} = Li\frac{di}{dt}$$

$$dW = Lidi$$

$$W = \int_0^w dW = \int_0^i Lidi = \tfrac{1}{2} Li^2 \qquad (57)$$

This is the total magnetic energy, W, in an inductance, L in henrys, carrying current i in amperes.

The density of energy, w, in a magnetic field is found by using the length, l, of a coil and its area, A.

$$w = \frac{W}{Al} = \frac{\tfrac{1}{2} Li^2}{Al} \qquad (58)$$

L can be expressed in geometrical terms as

$$L = \mu_0 n^2 Al \qquad (59)$$

where μ_0 is the permeability constant, a physical property of the magnetic material expressed in henrys per meter or volt·seconds / ampere·meter and n is the number of turns in the coil per unit length.

Ampere's law defines the magnetic induction, B, as:

$$B = \mu_0 i\, n. \qquad (60)$$

By substituting L in (59) and i in (60) into (58) the energy density stored, at any point where the magnetic inductor is B, is derived.

$$w = \tfrac{1}{2}\frac{B^2}{\mu_0} \qquad (61)$$

This equation is true for all magnetic field configurations.[116]

Current cryogenic technology has achieved magnetic inductances of around 8 webers/meter^2 or tesla, T. The

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[116] D. Halliday and R. Resnick, Physics for Students of Science and Engineering (New York: John Wiley & Sons, Inc., 1960), pp. 816-818.

amount of energy that could be put in a field of 8 tesla is not very large. Energy density increases as the square of the magnetic inductance, however, and eventually will represent a larger capacity. If magnetic fields of 50 tesla were readily achieved in large volumes this would compare in energy content to hydrogen compressed to 90 atmospheres. Ninety atmospheres of hydrogen is readily within current technology capabilities, but 50 tesla cryogenic fields in any significant volume are not.

It is possible to build DC transformers at cryogenic temperatures for transferring energy into and out of cryogenic magnetic fields, but our technical capabilities for doing this are limited to quite a small size.

Cryogenic magnetic fields for energy storage is theoretically possible, but they are not very promising in the foreseeable future from a technological standpoint.[117]

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[117]Hughes, "An Energy System for the Future", p. 1-3.

CHAPTER VI

SUMMARY

The cost of energy rises with the passing of each year. Recovery of fuels is becoming more difficult and expensive as the easy-to-obtain fuels are being depleted. The exploration for fuel is extending into remote areas like the Arctic regions, into deeper ocean waters, and to greater depths on land. Labor and material costs for both the recovery of fuel and the conversion of fuel to energy, as well as transporting costs, are rising. Foreign countries are forming cartels that can very effectively control the price of some energy fuels.

In addition to the cost, is the problem of shortages of energy fuels. Predictions vary greatly as to when, but people are generally coming to the realization that the energy fuels on this planet will run out someday. A more immediate danger perhaps is the possibility of losing our sources of fuels from overseas through political or hostile actions.

There are many sources of energy. The most common fuels are oil and coal. Both have enjoyed tremendous popularity, but their costs are increasing and new pollution control technology is required if the use of coal is going to increase. Nuclear energy can meet man's desires for energy for sometime to come, but the cost of constructing nuclear power plants and the cost of preparing nuclear fuel is high. In addition, there is a growing concern over the possibility of a nuclear accident or the possibility of dangerous nuclear materials falling into irresponsible hands. Hydroelectric generators have been used extensively, but their application is tied closely to certain topographical characteristics. Geothermal energy is also topographically oriented, but there are still many locations where this relatively new energy source can be used. Solar and wind energy require different technologies to produce usable energy, but the supply of these energies have many things in common. Both are predictable over the span of a year, but neither are predictable on a day to day basis. Both are available only at the discretion of nature and they are completely independent of man's demand for energy. All these, however; are promising as both near term and far term energy sources.

Wind energy, particularly, is ready to be tapped on a large scale today. The technology has evolved over centuries and the use of modern airfoil theory, stress analysis techniques, and power transmission equipment make the windmill an efficient machine. Other aerodynamic studies are finding ways to increase the energy density of the wind and it may become possible to surpass the "Betz limit" with certain windmill designs.[118]

There is a great deal of wind energy research being conducted today in the United States. The National Aeronautics and Space Administration is working on the vertical axis windmill at the Langley Research Center in Hampton, Virginia. They are also working jointly with the National Science Foundation, through findings from the Energy Research and Development Administration, to operate a test bed windmill at the Lewis Research Center at Plum Brook, Ohio to gain information on the operating performance and dynamics of large windmills. ERDA is also sponsoring development of the vertical axis windmill at Sandia Laboratories, New Mexico. Kaman Aerospace Corporation and General Electric Company are studying all possible concepts for large windmill generators as a result of ERDA's wind energy program.[119]

Oklahoma State University appears to be the college that is the most involved in wind energy development, but they are by no means the only one. Some other colleges involved with wind energy are: the University of Hawaii, Oakland University, the University of Wisconsin, the University of Toronto, Massachusetts Institute of Technology, and the University of Houston. Most of these colleges are

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[118] Black, "Advanced Turbine Designs Boost Wind-Power Potential", pp. 26-28, 30-32.

[119] Black, "Something in the Wind?" pp. 18-23.

involving the engineering students in student projects to harness the wind.

Despite predictions of success with wind energy, the utility companies are generally skeptical. They are not willing to invest in windmills unless the capital cost is under $500 per kilowatt of rated capacity at today's prices, have 20 to 30 year lifetimes, and have low operating and maintenance costs.

Judging from the budget of the Federal wind energy program of ERDA; $14 million in 1976 up from $200,000 in 1973; a lot of experts think the problems can be solved, and that someday windmills will be as plentiful on the landscape as high energy electric transmission towers are now.[120]

[120] Black, "Something in the Wind?" p. 18.

APPENDIX

Preliminary Design of a Windmill for A Single Family Dwelling

The house selected for this design exercise is an eight room two story house located in the Akron-Canton area of Ohio. Electrical loads include lights, radios, a color television, some small kitchen appliances, refrigerator, upright freezer, water pump, hot water heat circulation pump, clothers washer, electric clothes dryer, garage door opener, power woodworking tools. Within the next six months the addition of an electric oven (but not an electric range), and a dishwasher should be planned for.

Over the 30 month period from November 1974 to May 1977 a total of 15,550 kilowatt hours of electrical energy was consumed. Monthly average over this period is 518 kilowatt hours, however the average over the last eight months is 621 kilowatt hours. It is believed this jump is due mostly to an increased use of the water pump, clothes washer, and dryer, and that this is a temporary increase. For three years the November-December billing showed a high consumption of electricity, but the January-February billing did not. Apparently, seasonal considerations have only a slight impact on consumption.

The broad design of this installation must be determined first. Since the energy output will service a house that is normally connected to the utility company, the form of the energy should be similar to what the utility sells. This will eliminate the expense of converting the appliances to accept another form of electricity and will allow easy switching between the utility and windmill if necessary. Therefore the energy produced by the windmill will be AC electricity, 60 hertz, and 230 volts. A consumption of 500 kilowatt hours per month will be assumed. Also to be noted here is that purchased electricity can supplement the windmill.

Since the site of the windmill has been arbitrarily selected by the location of the house, the process of site selection has been eliminated. However, the wind characteristics of this site must be determined before the detailed design can begin.

TABLE 1

WIND SPEEDS AT VARIOUS SITES

Month	Akron - Canton 1968 20 year average	Cleveland 1972	Cleveland 1973
Jan.	5.3 m/s	5.9 m/s	5.7 m/s
Feb.	5.1	5.3	4.6
March	5.2	5.4	5.1
Apr.	5.0	4.9	5.1
May	4.2	4.3	4.4
June	3.8	4.3	3.8
July	3.4	3.6	
Aug.	3.3	3.7	
Sept.	3.7	4.1	
Oct.	4.1	4.3	
Nov.	5.0	4.3	
Dec.	5.2	4.8	

Lacking actual wind data for the installation site, the wind characteristics recorded at Akron-Canton will be used for this exercise.[121] Also assume that the average calm spell is three days, and that the wind blows 18 hours out of every 90.

For a small residential installation such as this one, battery storage seems to be the best, since it is simple and reliable. To determine the storage capacity the following calculations are made. The average consumption is 500 kilowatt hours per month or 16.7 kilowatt hours per day. Assuming 230 volt batteries with an efficiency of .8 the capacity in ampere hours needed is:

$$\text{battery capacity} = \frac{16.7\ \text{kW}\cdot\text{h/day} \times 3\ \text{days}}{.8 \times 230\ \text{V}} \times 1000\ \frac{\text{W}}{\text{kW}} = 272\ \text{A}\cdot\text{h}.$$

If the battery can be charged over an 18 hour period the charging current must be:

$$\text{charging current} = \frac{272\ \text{A}\cdot\text{h}}{18\text{h}} = 15\text{A}.$$

Generator capacity can now be calculated.

Generator capacity = 15A x 230V = 3450 W.

As a means of comparison, the exercise can be repeated using a 32 volt battery.

$$\text{Battery capacity} = \frac{16.7 \times 3}{.8 \times 32} \times 1000 = 1957\ \text{A}\cdot\text{h}.$$

Charging current = 1957/18 = 109 A.

Generator capacity = 109 x 32 = 3488 W.

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[121] Local Climatological Data (Washington: U.S. Government Printing Office)

Another possibility exists. Omit the expense of energy storage and use the windmill to reduce the amount of electricity purchased from the utility company. The average annual wind speed is 4.4 meters per second. Greater wind studies are necessary to confirm this, but assume the wind speed is greater than 6 meters/second for 40% of the time during 6 months of the year, and that it is greater than 6 meters/second for 15% of the time during the other 6 months.

By choosing 6 meters/second as the rated wind velocity of the installation the following calculations will indicate the size of windmill and generator needed:

$$\text{Generator capacity} = \frac{500 \text{ kW}\cdot\text{h/month}}{720 \text{ h/month}} \times 1000 \frac{\text{W}}{\text{kW}} = 700 \text{ W.}$$

The density of standard air is 1.22 k_g/m^3. Assume a power coefficient of .35.

$$\text{Windmill area} = A = \frac{2P}{C_p \rho v^3} = \frac{1400}{(.35)(1.22)(6)^3} = 15.2 \text{ m}^2$$

$$\text{Radius} = r = \sqrt{\frac{15.2}{\pi}} = 2.2\text{m.}$$

This installation would supply a portion of the electricity for the house. Automatic switching equipment would have to be provided to switch to the windmill generator when it was generating. Since the installation would be running in parallel to the power network they have to be synchronized. This can be accomplished by using an AC commutator generator with the power network supplying the excitation frequency.

A slight change in life style can produce an even greater savings. Greater utilization of the installation can be obtained by delaying the use of electrical loads, when possible, until the windmill generator is generating.

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