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COMPONENT SIZING FOR STAND-ALONE WIND-ELECTRIC GENERATING SYSTEMS: FREQUENCY AND TIME SPAN OF DATA NEEDED

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Abstract: This paper describes the development and application of a simple numerical algorithm for the design of a stand-alone wind-electric generating system to supply a given load in an area with known wind speed profile. The algorithm is described briefly and is applied for sizing the generating and storage components needed to meet the power demand of an average residence in a remote area with known wind speed profile. A discussion on the use of low frequency (hourly) and high frequency (15-minute) wind data, used for system design, and the time span of data needed are given using Weibull distributions.

I. INTRODUCTION

The ever increasing need for electrical energy, the limited fossil fuel resources needed for generation of conventional electrical power, and the global environmental concerns over the use of fossil fuels have opened new avenues for utilization of renewable energy resources. In particular, wind has been recognized as one of the most promising renewable energy sources[1,2]. Rapid advances in wind-electric generation technologies have lead to the increased use of wind turbine generators (WTG's), both in the form of distributed utility as well as stand-alone configurations.

One of the most promising markets for stand-alone wind-electric power generation is in remote homesteads, farms and ranch operations, where there is an appreciable distance between the load and the nearest utility distribution line. In such cases, the cost to supply the load with conventional utility-generated electric power or to upgrade the existing connection between the power distribution system and the load can be significant. It may be economically beneficial to consider a stand-alone renewable generating system such as wind, photovoltaic (PV), or a hybrid wind-PV system, as opposed to constructing a line extension from the nearest distribution line to transport utility-generated power to the residential/farming/ranching unit. However, it is essential that the capacity of the stand-alone generating system components be selected properly to ensure reliable generation that can supply the load economically[3,4,5]. These papers propose linear programming models to design integrated renewable generating systems and to arrive at an optimal mix of system components.

This paper presents the development of a simple iterative algorithm for the design of a stand-alone wind-electric generating system based on energy balance[6]. The algorithm is then used for component sizing for a generating system to supply the power demand of an average home assumed to be located in a remote area in south-central Montana. The hourly wind data (averaged over three years, 1993-1996) have been used.

The paper will then present a discussion on the frequency of wind data (i.e., hourly and 15-minute data) used for component sizing and will give a comparison of Weibull probability density functions for hourly and 15-minute wind data used over a three-year time span. It will also discuss a sufficient time span of data needed for system design.

It is shown that although both 15-minute and hourly data can be used for sizing the components of the generating systems, considering the intermittent nature of wind in a given area, the hourly data over a one-year time is sufficient to use for system design. Waiting for more accurate data to be obtained over a longer time span may yield only slightly more accurate results. Using the Weibull distribution functions, it is shown that it may not be worth the effort to wait for longer than one year of data for sizing the system components.

II. THE STAND-ALONE CONFIGURATION

A block diagram for the stand-alone generating system configuration is shown in Fig. 1. The storage batteries will supply power to the load when wind-generated power is not sufficient to supply the load. The backup diesel generator will be used during the periods when the wind-generated power is not sufficient and the batteries' charge is reduced to less than a certain percentage of their full capacity. Considering the cost of operation of the diesel generator and its environmental effects, the operation of the backup generator is to be kept to a minimum. The operation of the diesel generator, battery voltage regulator, rectifier and inverter, and the DC voltage controller will be controlled by a centralized controller.

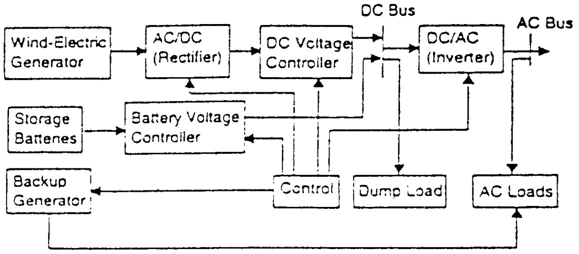

Fig. 1 Stand-alone wind-electric generating system configuration.

III. COMPONENT SIZING

In this section, an iterative algorithm is described for obtaining estimates of the wind generator and storage capacities needed for the stand-alone system of Fig. 1 to satisfy the power demand of a given load. The algorithm uses the hourly average wind speed and power demand to determine the wind generation and storage capacities required to meet the demand. The total annual cost to the customer (*Fc*) for the system can then be calculated using the capital and the maintenance costs. *Fc* is the sum of the annual cost of the capital over the life of the generating system (*Cc*) and its annual maintenance cost (*Cm*).

$$Fc = Cc - Cm \tag{1}$$

The above costs can be written as the sum of the annual costs of the wind turbine, storage, and backup generation, as follows:

$$Cc = Cc_{wind} + Cc_{store} + Cc_{backup} \tag{2}$$

$$Cm = Cm_{wind} + Cm_{store} + Cm_{backup} \tag{3}$$

Fc is constrained to minimize the magnitude of the net power flow ΔP, where ΔP is the difference between the generated power (P_{gen}) and the demanded power (P_{dem}) over a given period of time (i.e., 24 hours).

$$\Delta P = P_{gen} - P_{dem} \tag{4}$$

The total generated and demanded energy (W_{gen}, W_{dem}) over a 24-hour period can be written in terms of the wind-generated power and the power demand as follows:

$$W_{gen} = \sum_{n=1}^{24} [(\Delta T)(K_w P(n)_w)] \tag{5}$$

$$W_{dem} = \sum_{n=1}^{24} [(\Delta T)(P(n)_{dem})] \tag{6}$$

where, $P(n)_w$ is the power generated by a specified wind turbine, K_w is the number of wind turbines used, n is the sampling time (hour of day), and ΔT is the time between the samples (in this case one hour).

In order for generation and demand to balance over a given period of time, the curve of ΔP versus time (i.e., the net power flow) must have an average of zero over the same time period. Note that positive values of ΔP indicate the availability of wind-generated power, and negative ΔP indicates generation deficiency. In the iterative procedure, the number of WTG's will be increased until the sum of ΔP's over 24 hours crosses zero (going from negative to positive).

The equation for net energy exchange (ΔW) as a function of time can be obtained by integrating ΔP.

$$\Delta W = \int \Delta P dt = W_{gen} - W_{dem} \tag{7}$$

The energy curve of equation (7) can be used to find the required storage capacity for the stand-alone generating system. On an average day, the battery is required to cycle between the positive and negative peaks of the energy curve. Therefore, the battery should have a capacity at least equal to the difference between the positive and negative peaks of the energy curve (see Fig. 6).

$$\textit{Required Storage Capacity} = Max\int\Delta P dt - Min\int\Delta P dt \qquad (8)$$

For this type of application, batteries designed specifically for cycling should be used. In order to obtain the best life expectancy for these batteries, they should be retained near full charge, or return to this status as quickly as possible, and they should not be cycled below more than 80% of their rated capacity[7].

The iterative procedure for selecting the number of wind turbines and estimating the storage capacity for a specific load profile is summarized in the flow chart of Fig. 2.

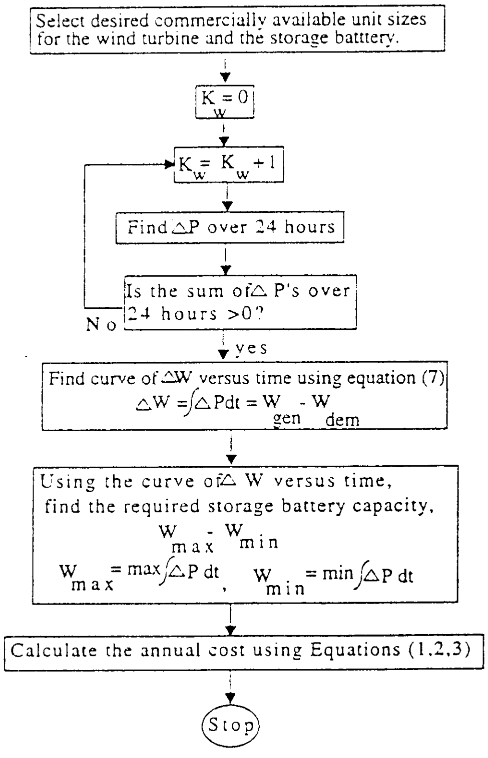

Fig. 2 Flow chart for the iterative procedure.

IV. CASE STUDY

The above procedure was used to estimate generation and storage capacities of a stand-alone wind generating system to supply electrical power to a house with typical power demand (not including electric water heater load). house is assumed to be located at a site in a remote ar South-Central Montana for which wind speed dat been recorded since 1993. Fig. 3 shows the annual h average wind speed for the site for the years 1993-96. hourly average power demand of an average house i Pacific Northwest, taken from[8], was used in the stud is shown in Fig. 4.

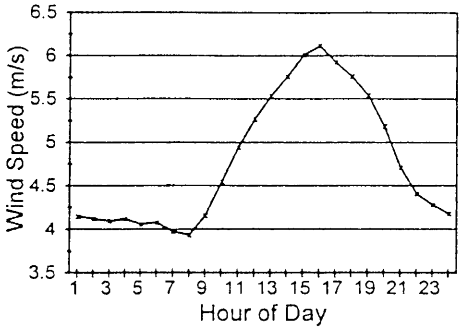

Fig 3. Annual hourly average wind profile for the studied.

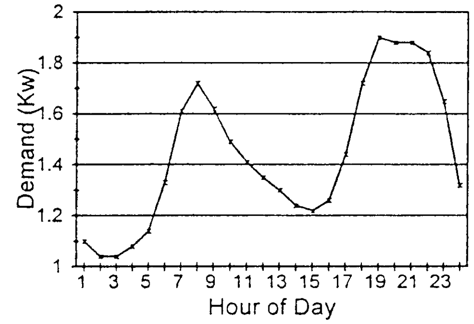

Fig 4. Hourly average power demand of an averag home in the pacific northwest.

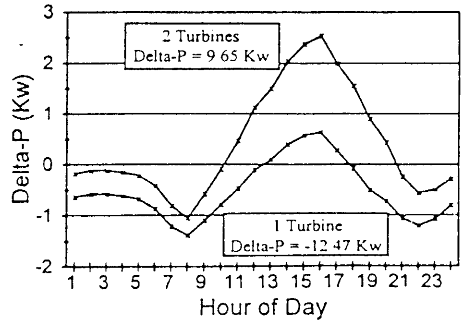

Fig 5. Average daily ΔP using 10 kW WTG's.

10 kW Bergey wind turbines, 6 V deep cycle batteries, and a 3.2 kW backup diesel generator were used. When only one 10-kW turbine was used, the sum of ΔP's (over 24 hours) was negative. However, with two turbines, the sum became positive. Fig. 5 shows curves of ΔP versus time for the average house when one and two 10-kW turbines were used to supply power to the house. Therefore, according to the flow chart of Fig. 2, two wind turbines were used to satisfy the house demand. The storage capacity needed can be obtained from the energy curve (ΔW versus time). Fig. 6 shows the energy curve when two 10-kW turbines were used to supply the load. From this figure, and according to equation (8), the energy through which the battery cycles is obtained to be:

$$\Delta W_{max} - \Delta W_{min} = 11.22 - (-3.74) = 14.96 \text{ kWh}$$

1.5 kW turbines were also used in the simulation study. The number of turbines used was incremented (by one in each iteration) until the sum of ΔP's over 24 hours became positive. This condition occurred at $K_W = 13$. Table 1 shows the sum of ΔP's over 24 hours for different number of turbines used and Fig. 7 shows three curves of ΔP as a function of time of day for 5, 10, and 13 turbines. It is clear from the table that the sum of ΔP's is negative for $K_W \leq 12$ and becomes positive for $K_W = 13$. It is also clear from Fig. 7 that curves of ΔP versus time have negative average for $K_W = 5$ and for $K_W = 10$. However the average value of the curve turns positive for $K_W = 13$.

Turbines	ΔP
1	-31725
2	-28870
3	-26015
4	-23160
5	-20305
6	-17450
7	-14595
8	-11740
9	-8885
10	-6030
11	-3175
12	-320
13	2535

Table 1. Sum of ΔP's over 24 hours.

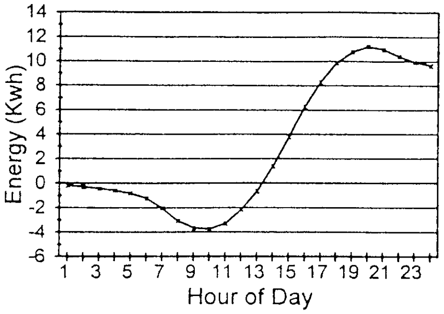

Fig. 6 ΔW versus time for 2 10-kW WTG's.

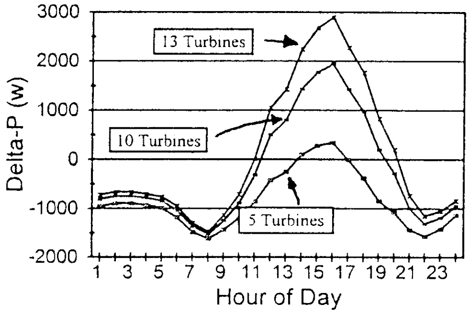

Fig. 7 Average daily ΔP using 1.5 kW WTG's.

V. WIND DATA FOR SYSTEM DESIGN

To determine the frequency of the wind data (i.e. hour average versus 15-minute data) and the time span which suitable for use for the above design procedure, curves Weibull probability density functions for the wind spee data were used. Assuming wind speed distribution to a Weibull distribution, its probability density function given by[9],

$$f(u) = \frac{k}{c} . \left(\frac{u}{c}\right)^{k-1} . \exp\left[-\left(\frac{u}{c}\right)^{k}\right] \tag{9}$$

where, u is the wind speed, $k = (\sigma/u)^{-1.086}$ is the shap factor (dimensionless), $c = \bar{u} / [\Gamma(1+1/k)]$ is the sca factor in unit of wind speed used, σ is the standar deviation of the wind speed distribution, $\bar{u} = c \int x^{1/k} e^{-x} \, dx$ the mean of *the probability density function* $f(u)$, and th gamma function Γ is defined by:

$$\Gamma(y) = \int e^{-x} x^{y-1} \, dx$$

Weibull fits were obtained for the wind speed data available for the site under study, between 1993 and 1995. Both 15-minute and hourly data were used. These distributions and their corresponding constants are shown in Fig. 8. It is clear from this figure that the corresponding constants of the two distributions are very close to one another; the two curves are almost on top of each other. Therefore, the hourly data would be as suitable to use for the proposed design procedure as the 15-minute data.

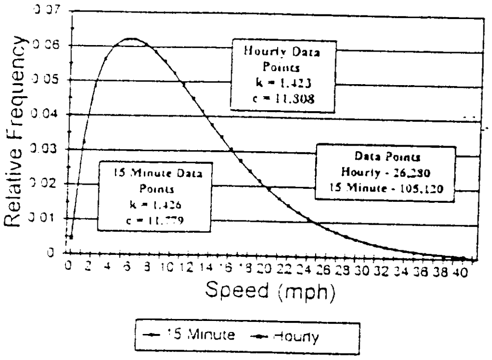

Fig 8. Comparison of Weibull distributions using hourly and 15-minute wind data (1993-95)

Weibull fits to hourly average wind data for the site were also obtained for each year (1993, 94, 95). These fits were compared with the three year (1993-95) hourly average Weibull fit, as shown in Fig. 9. As shown in this figure, the parameters of the Weibull distribution for different years (93, 94, 95) are very close to the corresponding parameters of the Weibull fit when three years worth of data are used.

Weibull distributions were also obtained for the wind data for different months of each year for comparing with the constants of the Weibull fits for a full year of wind speed data. Table 2 shows the constants for different months in 1995 for both 15-minute and hourly average data. It is noted from Table 2 that the corresponding constants of the Weibull fits differ from month to month when compared with the constants of the Weibull fits for the years 1993, 94, 95 (shown in Fig. 9). Therefore, the data over a one-year time span is more reliable than monthly data to use for the proposed design procedure.

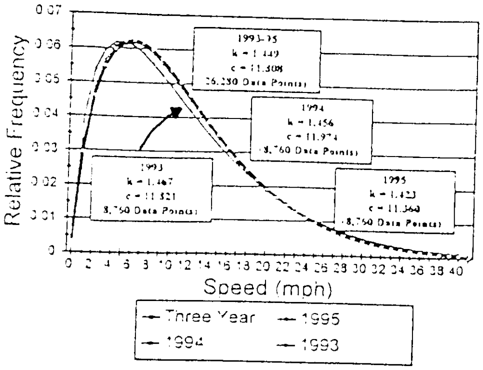

Fig. 9 Comparison of Weibull distributions using yearly and three-year hourly average wind data.

	Hourly Average Data Points		15 Minute Data Points	
	k (shape)	c (scale)	k (shape)	c (scale)
January	1.585	9.931	1.484	9.864
February	1.496	13.544	1.453	13.481
March	1.331	11.823	1.294	11.766
April	1.480	12.023	1.460	12.179
May	1.318	11.554	1.283	11.497
June	1.565	10.300	1.473	10.227
July	1.542	10.525	1.436	10.426
August	1.264	10.213	1.204	10.094
September	1.393	9.749	1.342	9.680
October	1.685	14.448	1.622	14.376
November	1.373	11.951	1.322	11.864
December	1.511	11.826	1.533	10.165
Average	1.461	11.490	1.413	11.304

Table 2. Comparison of Weibull parameters for different months.

VI. CONCLUSIONS

The development and application of a simple numerical algorithm for the design of a stand-alone wind-electric generating system was presented in this paper. The algorithm was used for component sizing of a stand-alone system to meet the power demand of an average residence (in a remote area in south-central Montana) with known wind speed profile. Both hourly and 15-minute wind data were used in the study, and the results obtained in both cases were very close to each other.

Weibull distributions were obtained for the recorded wind data. It was noticed that the Weibull fits were very close when hourly and 15-minute wind data were used both for a three-year time span as well as a one-year time span.

Given the stochastic nature of wind, and based on the results presented in this paper, hourly average wind data, taken over a one-year time span, could be sufficient to use for sizing the components of a stand-alone wind generating system using the algorithm proposed in this paper.

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