N83 19248 D17

LONG-TERM ENERGY CAPTURE AND THE EFFECTS OF OPTIMIZING WIND TURBINE OPERATING STRATEGIES

A. H. Miller and W. J. Formica
Pacific Northwest Laboratory(a)
Richland, Washington 99352

ABSTRACT

One of the major factors driving the evolutionary design of wind turbines is the cost of energy (COE). The COE for electricity produced by any means is based on three primary factors: capital costs plus operating and maintenance (O&M) costs divided by the number of kilowatt hours produced per year. Obviously an increase in production of energy has the positive effect of decreasing the cost of energy produced by a wind turbine.

A research effort has been established to determine the possible methods of increasing energy capture without affecting the turbine design. The emphasis has been on optimizing the wind turbine operating strategy. The operating strategy embodies the startup and shutdown algorithm as well as the algorithm for determining when to yaw (rotate) the axis of the turbine more directly into the wind.

Using data collected at a number of sites, the time-dependent simulation of a MOD-2 wind turbine using various, site-dependent operating strategies has provided evidence that site-specific fine tuning can produce significant increases in long-term energy capture as well as reduce the number of start-stop cycles and yawing maneuvers, which may result in reduced fatigue and subsequent maintenance.

INTRODUCTION

The economic viability of wind power in the current and future market is a multifaceted question and may be a function of the intended use by a utility and the utilities' own-operating strategy. These factors aside, the optimization of a large wind turbines' computer controlled operating strategy could produce the desirable effect of increased energy production and decreased wear on the machine. At a recent Wind

---

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830 by Battelle Memorial Institute.

Turbine Designers Workshop held in Seattle, several engineers from industry emphasized that the primary factor to be reconciled with in designing a wind turbine is cost of electricity (COE). This cost is estimated on the basis of interest rate on money borrowed, the capital equipment cost, the annual operation and maintenance cost and the energy produced.

Current estimates of the cost of capital (or actually cost of borrowing money) to an investor-owned utility have risen to 20 to 22%. The O&M costs for large wind turbines, such as a MOD-2, are estimated to be between $20 and 25 thousand per year. Using the hundredth-unit cost for a MOD-2 wind turbine and an energy capture of 6 GWh per year, we can calculate the cost of electricity as:

$$\text{C.O.E.} = \frac{0.20\ (\$2.0 \times 10^6) + \$25{,}000}{6 \times 10^6\ \text{kWh}} = \$0.07\ \text{kWh}$$

It is obvious from the form of the equation that any percentage increase in energy capture results in an equal percentage decrease in COE.

The inherent decrease in COE became the motivation for this and several ancillary studies to determine ways to optimize wind turbine operating strategies as well as providing guidance to candidate site wind measurement strategies and recognition of the scales of atmospheric motion which affect wind turbine operations.

BACKGROUND

Research in wind energy seems to have been focused on two distinct yet different scales or areas: wind resource assessment and wind turbine dynamics. The end-user, in almost all cases a utility, has requirements and standards which are in a totally different time frame. The areas which have received emphasis can easily be equated to scales of atmospheric motion illustrated in Figure 1.

Resource assessments are typically based on a monthly, seasonal, and/or annual bases. This corresponds to space scales of thousands of kilometers and would fall into the lower left hand portion of Figure 1. Machine dynamics or loads on the other hand, are most concerned with second to minute and at most, hourly <u>average</u> time scales. The time frame between a few seconds and a month or slightly less are of major concern to an electricity generating agent. Since a number of major and frequently occurring atmospheric phenomena occur in that "window" and could impact a utility, a model, or more appropriate, a simulation of the current generation of large wind turbine, the MOD-2, was developed.

THE MODEL

First reported a year ago [1] the original model has evolved but only in terms of output products. Figure 2 is a narrative flow diagram of

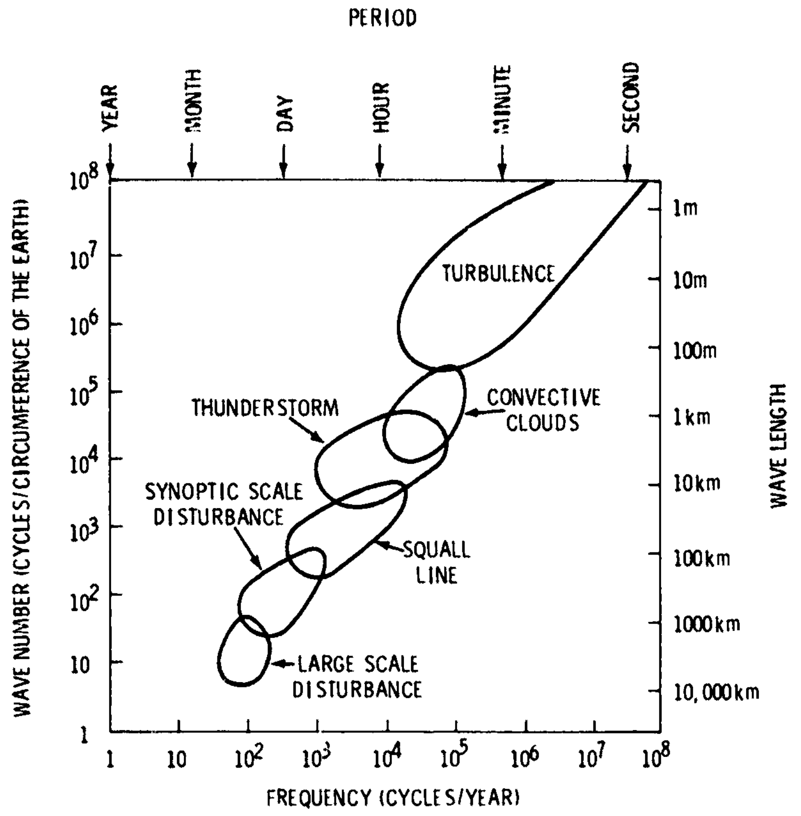


FIGURE 1. SCALES OF SOME COMMON ATMOSPHERIC PHENOMENA IN TERMS OF FREQUENCY, PERIOD, WAVELENGTH AND WAVE NUMBER (MODIFIED FROM MEYER [2])

the MOD-2 simulation. The attributes of this simulation are that it takes into account all of the losses incurred by the MOD-2 in its start up, yawing and shut down strategy as well as seasonal atmospheric density depending on the site under investigation and losses due to wind being off-axis. Currently the program is set up to run using the DOE 2 min candidate site data since they consist of a variety of high wind resource sites with continuous data for as much as 2 to 2-1/2 yr. Though 2 min instantaneous data may not be an accurate representation of the true 2 min average wind speed and therefore may give somewhat biased short-term statistics, the assumption that the instantaneous value is representative of the 2 min average wind speed will not cause any significant effects in the long run.

The MOD-2 simulation model is initialized in an interactive mode. Since all the candidate site data are in an existing file, the site and period of interest are input as well as variations one may want to impose such as changing the maximum directional (yaw) error or motoring the generator. Figure 3 is a presentation of a typical interactive session. Upon execution the first data sample is read in and some quality checks are made to assure that the data is reasonable. Assuming the data is good and the wind speed ≥ 6.26 ms^{-1}, the program determines the length of time over which the wind speed must be integrated before a "startup" can proceed. The time required is a function of the

ORIGINAL PAGE IS
OF POOR QUALITY

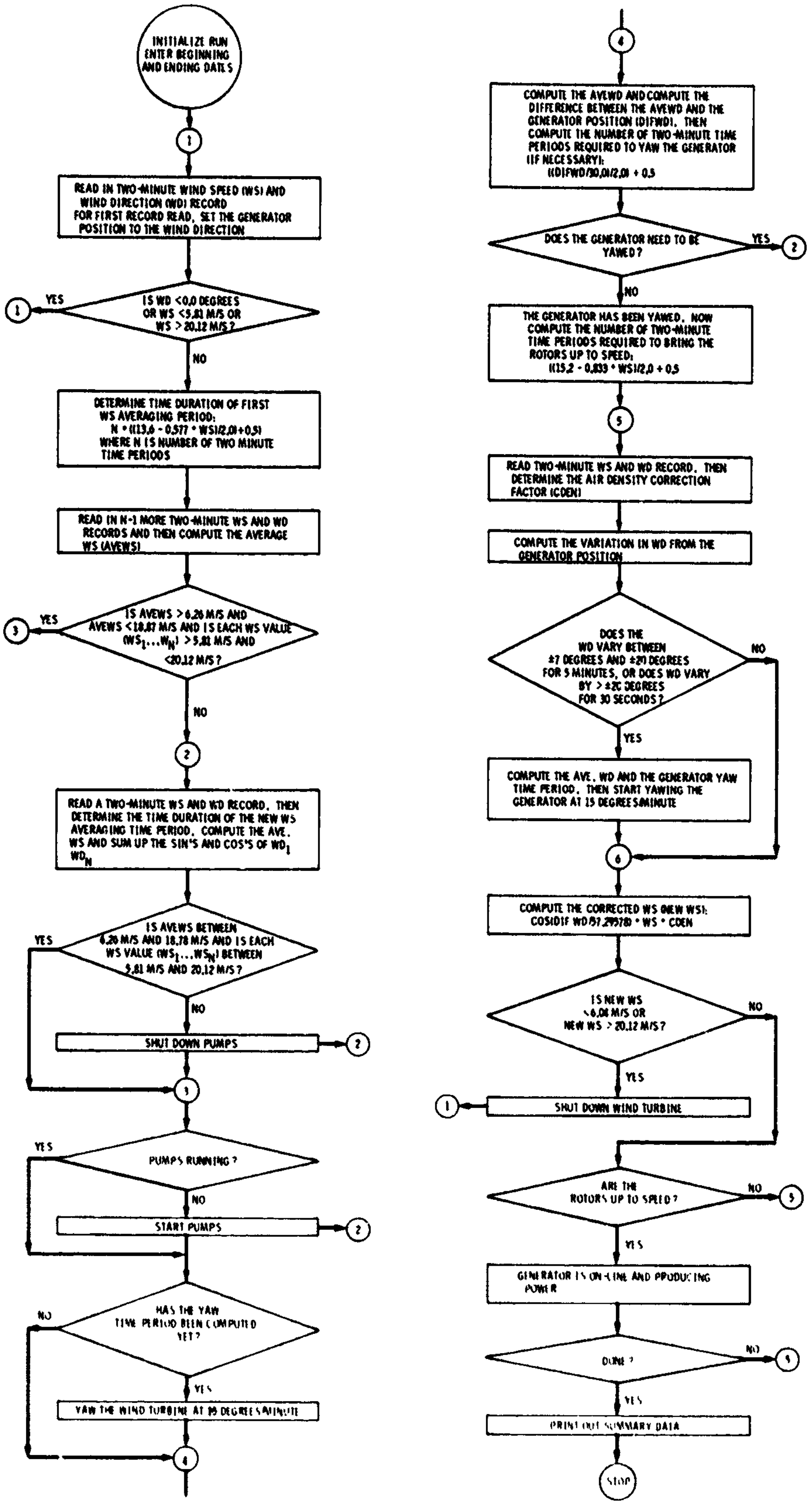
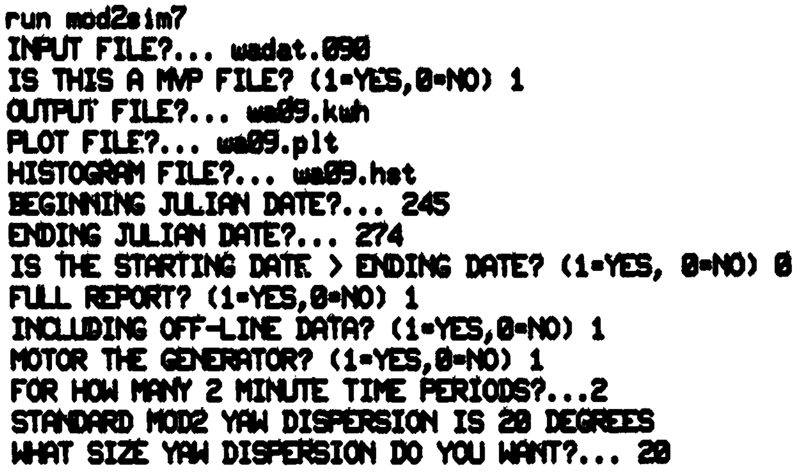


FIGURE 2. FLOW DIAGRAM OF THE MOD-2 SIMULATION MODEL



```
run mod2sim7
INPUT FILE?... wadat.090
IS THIS A MVP FILE? (1=YES,0=NO) 1
OUTPUT FILE?... wa09.kwh
PLOT FILE?... wa09.plt
HISTOGRAM FILE?... wa09.hst
BEGINNING JULIAN DATE?... 245
ENDING JULIAN DATE?... 274
IS THE STARTING DATE > ENDING DATE? (1=YES, 0=NO) 0
FULL REPORT? (1=YES,0=NO) 1
INCLUDING OFF-LINE DATA? (1=YES,0=NO) 1
MOTOR THE GENERATOR? (1=YES,0=NO) 1
FOR HOW MANY 2 MINUTE TIME PERIODS?...2
STANDARD MOD2 YAW DISPERSION IS 20 DEGREES
WHAT SIZE YAW DISPERSION DO YOU WANT?... 20
```

FIGURE 3. A TYPICAL CRT DISPLAY OF THE INTERACTIVE SESSION TO RUN THE MOD-2 SIMULATION. THE CAPITALIZED WORDS ARE THE COMPUTER GENERATED QUESTIONS, THE SMALL LETTERS ARE THE INPUTS.

wind speed and if the wind speed increases sufficiently during the integration period, that period is shortened commensurately. If the average speed is inadequate or "limit" criteria have been exceeded then the wind speed integration is reinitialized. If on the other hand all criteria have been met for a startup the program tells the "turbine" to start its hydraulic pumps. This operation on a real MOD-2 takes 2 min between command and the hydraulic system being ready to operate. The next step is to yaw the turbine into the wind (± 5°) except for the very first startup at which time the turbine is assumed perfectly aligned with the first wind direction. In reality a MOD-2 wind turbine can be yawed 15° min^{-1} and therefore if the yaw error is less than 30° the model simply assumes that the yaw manuever has occurred between successive data points and prints out such a message. Once any yaw error has been accounted for and the hypothetical "brake" released, the model computes the length of time required for the turbine blade to come up to synchronous speed and begin generating electricity. Once on line the model will continue to simulate all the yaw manuevers as well as the power out for as long as $6.04\ \text{ms}^{-1} < \text{wind speed} < 20.12\ \text{ms}^{-1}$.

Figure 4 shows the characteristic curve of MOD-2 power out versus wind speed. In Figure 4 it appears there are two cut-in speeds. In fact, one is the cut-in speed (14 mph) while the lower speed (13.5 mph) is actually the low speed cut-out. The MOD-2 is unique in that it is the first multimegawatt, upwind turbine thereby casting the nacelle mounted control anemometers in a "wind shadow" once the turbine blades begin to rotate. Because of this, once on line, the turbine becomes its own control anemometer. Low speed shut down occurs not when a minimum apparent wind speed is reached but rather when the turbine output power reaches < 125 kW. To simulate the MOD-2 the wind data are used to calculate power out by the polynomial:

$$P_{kW} = -541.0 - 93.5\ V + 39.2\ V^2 - 0.909\ V^3$$

**ORIGINAL PAGE IS
OF POOR QUALITY**

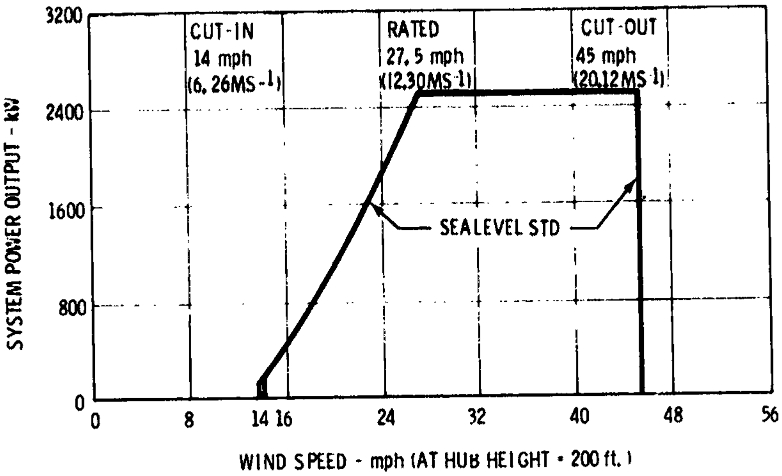


FIGURE 4. OUTPUT POWER CHARACTERISTICS VERSUS WIND SPEED FOR A MOD-2

to the limit $P_{kW} = 2500$. Above 12.3 ms^{-1}, rated on the MOD-2, the simulation maintains constant power up to a wind speed of 20.12 ms^{-1} above which the turbine is cut off line and brought to a stop. On a high speed cut off, the wind speed average must be below approximately 18.3 ms^{-1} for at least 4 min before the turbine is brought back on line. During those periods when the simulated MOD-2 is online and generating the model is keeping track of the wind direction and the actual yaw angle of the wind turbine. If the average yaw error is between ± 7° and ± 20° the turbine will be yawed directly into the wind after 5 min. If the error exceeds ± 20° for 30 s a correction is applied immediately. In these cases 6 min and 2 min are used respectively due to the data base. Though this appears to introduce some error the time required for the wind turbine to be yawed (at 15° min^{-1}) uses up the majority of the time difference in either case. Also during periods when the simulated turbine is online a cosine correction for the yaw error is applied to the wind speed before power out is computed.

Atmospheric density effects are applied seasonally. These were calculated from NASA Standard Atmosphere data. The density correction is only applied to the power producing wind but not to the wind speed data prior to power production. Since both cup and propeller anemometers are zero-balance devices they have been shown to be essentially unaffected by density at least up to altitudes well above any anticipated turbine site. Therefore the startup strategy would be unaffected unless it were intentionally modified but the turbine output would be reduced as a function of density.

APPLICATION OF THE MODEL

During the evolutionary development of the MOD-2 simulation model it was applied to diverse candidate site data. Output products include (if desired) a hard copy minute-by-minute account of the status of the MOD-2 for each datum. Analysis and interpretation of such a product led to the concept of computer optimization of large wind turbine operating strategies. As described in the preceeding section the MOD-2 simulated operating strategy accounts for the following:

Cut-in - the time between initialization and power generation is in three steps: 1) integrating the wind speed data before turning on the hydraulic pumps; 2) turning on the pumps and yawing the machine into the wind and 3) determining the length of time required for the rotor blade to reach synchronous speed.

Yaw manuevers - also a function of time, handles the modelled positioning of the turbine with respect to the wind direction and reduces the power out by reducing the apparent wind speed by the cosine of the error.

Turbine shutdown - occurs when power out drops below 125 kW or the wind speed corrected for density exceeds 20.12 ms^{-1}.

Obviously no modification of the design of a MOD-2 could be anticipated or tolerated in modifying the operating strategy. The initial step was to run the model for a complete year at a number of sites. Five sites were chosen on the basis of different topography and/or somewhat unique wind regimes. The sites chosen were, Holyoke, MA, Ludington, MI, Kingsley Dam, NB, Clayton, NM, and San Gorgonio Pass, CA. Results of three of these simulations are shown in Figure 5. Subsequently single months from each site characterized by the smallest amount of missing data, were picked for further testing.

Investigation of the distribution of yaw errors led the authors to believe that reducing or increasing the yaw error limits may serve to increase energy production without prohibitive increases in the number of yaw manuevers. The simulation was once again run on each site for a selected month varying the allowable maximum yaw error from the base 20° to 10°, 15°, and 25°. The results are tabulated in Table 1, Section A.

The second set of modifications involved the startup strategy. The standard (base case) algorithm for determining the wind speed integration period is a function of wind speed varying linearly from 10 min at 6.26 ms^{-1} to 2 min at 20.12 ms^{-1}. This was modified such that the 2 min upper limit occurred at rated wind speed, 12.3 ms^{-1}. Further, besides running the model with the original 20° yaw error limit a second set of runs with a 10° yaw error limit was run. Results of these tests are given in Table 1, Section B.

The third sequence of tests had a dual purpose. Start/stop cycles and yaw manuevers, however necessary, are believed to be large contributors to fatigue and maintenance. In an attempt to reduce false starts and possibly increase energy production simultaneously, the wind speed integration period at cut-in speeds was increased to 12-min. Further, both 10° and 20° upper yaw error limit cases were run for comparison. The results can be seen in Table 1, Section C.

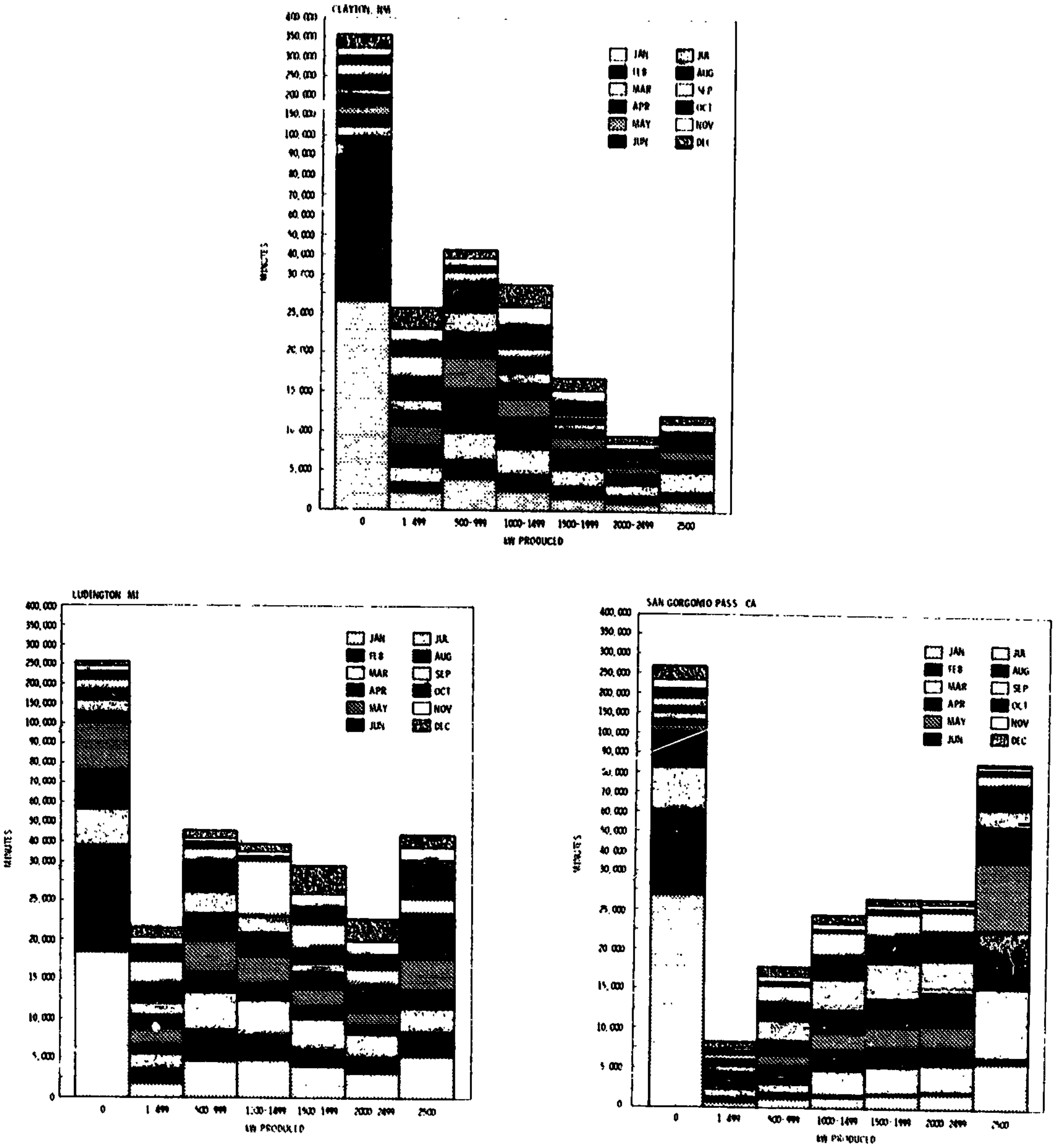


FIGURE 5. CUMULATIVE MONTHLY POWER PRODUCTION HISTOGRAM FOR 1 YR AT THREE SITES. NOTE: SCALE CHANGES AT 30,000 AND 100,000 MIN.

TABLE 1. MOD-2 SIMULATION RESULTS

	A				B		C		D	
	10°	15°	20°	25°	10°	20°	10°	20°	Free-Wheeling	Motoring
MA Jan										
kWh	351088	355611	355203	355708	355708	358688	354756	357791	388090	379464
Start/Stops	114	108	109	110	121	117	119	114	44	43
# Yaws	2091	1212	768	586	2149	795	2117	794	860	895
False Starts	47	43	43	41	44	42	38	35	25	15
NM Dec										
kWh	219688	219590	220114	219746	222218	222561	219783	220300	231461	238182
Start/Stops	181	182	180	183	193	189	179	180	135	92
# Yaws	1091	530	343	303	1154	355	1106	340	379	461
False Starts	346	348	349	346	364	368	314	311	322	258
MI Jul										
kWh	145499	146060	146193	145707	147806	148159	145414	146132	161088	163187
Start/Stops	130	129	129	131	136	136	123	122	86	62
# Yaws	714	389	260	203	753	253	703	249	302	359
False Starts	121	120	119	119	119	115	111	109	97	84
NB Jan										
kWh	311459	311382	311078	311996	315471	316033	311260	310857	356731	337311
Start/Stops	158	167	169	168	179	178	167	168	111	84
# Yaws	1454	644	409	365	1470	414	1439	407	516	565
False Starts	123	124	123	121	130	128	110	111	94	74
CA Nov										
kWh	140949	141315	141067	141044	142769	142756	142655	142774	158185	145422
Start/Stops	40	40	40	40	43	43	45	45	27	26
# Yaws	566	271	155	131	575	157	564	157	172	200
False Starts	50	49	49	49	61	62	43	42	46	45

A - Results from varying the maximum yaw error parameter (20° is the standard design value)
B - Results of reducing the startup integration period
C - Results from increasing the low wind speed startup time
D - Results with free-wheeling and "motoring" allowed (both cases at 20°)

The last two attempts to modify the MOD-2 operating strategy are of a somewhat speculative nature and, though quite different in philosophy are quite similar in nature. Both cases were run with only the 20° maximum yaw error (base case). The differences can be identified by equating the modifications to a passive and an active method of accomplishing the same goal. In the passive case the low speed cut-off (6.04 ms^{-1}) was invoked by a two-sample (4-min) average rather than a single datum while the active method utilized the synchronous generator as a motor to keep the rotor speed up. While the passive case was equivalent to allowing the turbine to free-wheel for short periods, the active case used power equivalent to a 200-hp electric motor (P.F. = 0.8) to keep rotor speed up. In this case the power consumed in the "motoring" mode was subtracted from the accumulated power produced. In the motoring case the turbine was allowed to motor for up to 4-min at every shutdown. If in fact the turbine experienced positive torque-winds $\geq$ 6.26 ms^{-1}--the motoring was immediately cut-off. While it is known that a MOD-2 could be operated in the motoring mode, the passive or free-wheeling mode may in fact add unnecessary stresses to the turbine and support structure.

Results from the five sites for both modes of operation are listed in Table 1, Section D.

DISCUSSION

During the course of this study a number of unexpected results surfaced which, though somewhat outside the scope of this report, are worth reporting. Though the MOD-2 simulation model is undoubtedly subject to the vagaries of the 2 min instantaneous data, the only minor effect is likely to be in the number of low speed start/stop cycles. Otherwise for periods of the order of less than a week and longer the effects of the data should be minimized if distinguishable at all. As mentioned earlier the first step in this study after development of the computer model was to pick some sites and run a base case "bench-mark" against which all variations of the operating strategy could be compared. The result of each site's run included annual cumulative total kilowatt hours produced. These results did not account for missing data. Assuming the missing data over the period of 1 yr were scattered randomly throughout the whole sample the resulting total was normalized by the ratio of time the machine was "on-line" versus "off-line" (a percentage) multiplied by the total time missing multiplied by the site average power and adding that to the power produced. Figure 6, the power duration curves for the five sites, also gives the resulting GWh produced using the site hourly average wind speeds. The annual power production for these sites resulting from the annual operating strategy simulation are shown in Table 2.

The dot on each power duration curve is the annual average power for the site. Figure 7 shows the normalized wind frequency distribution and the site annual average wind speed and average power derived from the hourly average wind speed. Table 3 gives these values and the values calculated from the MOD-2 simulation model.

ORIGINAL PAGE IS
OF POOR QUALITY

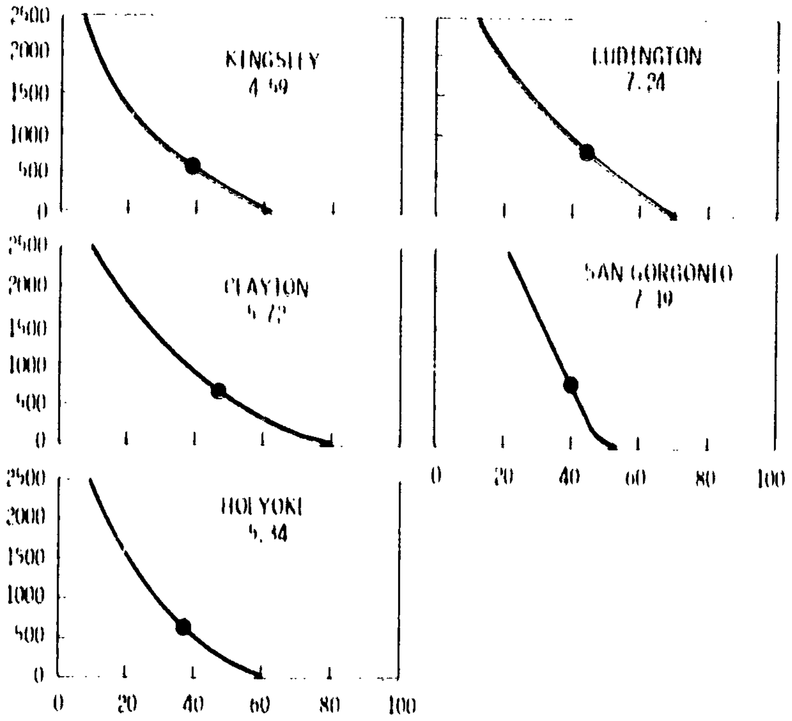


FIGURE 6. HOURLY DISTRIBUTION OF POWER OUT OF A MOD-2 BASED ON DATA FROM 45.7 M HEIGHT. THE NUMBER BELOW THE SITE NAME IS THE NUMBER OF GWh (10^6 kWh) OF ENERGY PRODUCTION ANNUALLY. THE ABSCISSA IS THE PERCENT TIME THE TURBINE IS EQUAL TO OR GREATER THAN THE POWER LEVEL ON THE ORDINATE.

TABLE 2. ANNUAL MOD-2 POWER PRODUCTION COMPUTED TWO WAYS

Site	Hourly Average (GWH)	Operating Strategy Simulation (GWH)	Difference (%)
Kingsley, NB	4.59	2.93	-36
Clayton, NM	5.72	2.87	-51
Holyoke, MA	5.34	2.90	-46
Ludington, MI	7.24	6.27	-14
San Gorgonio, CA	7.19	7.60	+ 6

The interesting point evidenced in Figures 6 and 7 and Tables 2 and 3 is that the resulting differences appear to be uncorrelated with topography, altitude or geographic location. The results obtained by modifying the operating strategies may offer a clue. Examining Table 1 on a site by site basis one notes that at the Holyoke, MA site the greatest gain in power (with the exception of the free-wheeling and motoring cases) comes from the shorter integration time at startup (Section B). Though there is a concomitant increase in number of yaws, that increase is tolerably small. The increase in power leads one to believe that the characteristic wind rises in velocity fairly rapidly from less than

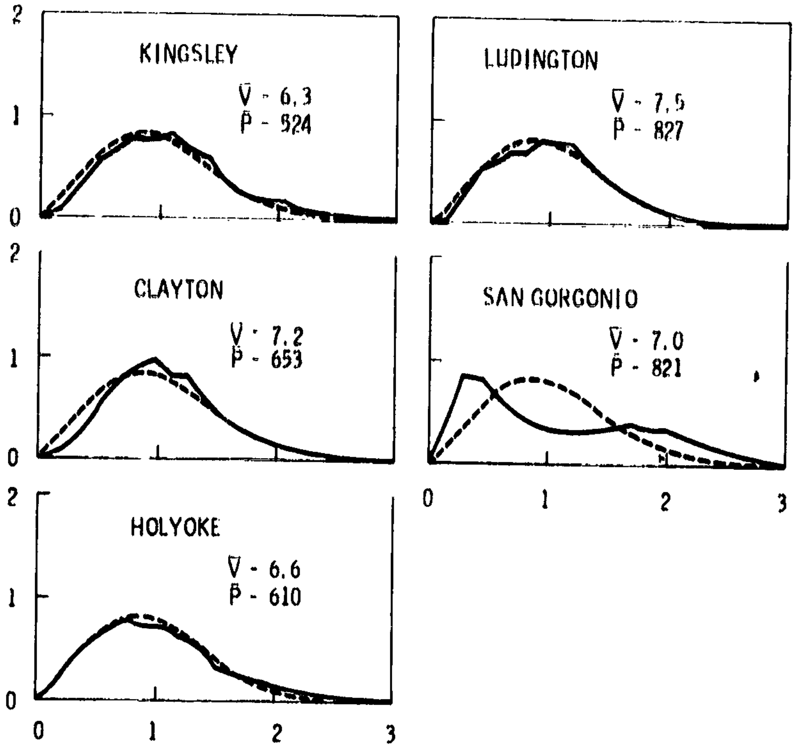


FIGURE 7. NORMALIZED FREQUENCY DISTRIBUTIONS OF HOURLY WIND SPEED DATA (SOLID LINE) AND THE NASA MODIFIED WEIBULL DISTRIBUTION BASED ON THE ANNUAL MEAN WIND SPEED (DASHED LINE). $\bar{V}$ IS THE ANNUAL MEAN WIND SPEED (ms $^{-1}$) AND $\bar{P}$ IS THE AVERAGE ANNUAL WIND POWER(kW).

TABLE 3. AVERAGE POWER FROM A MOD-2 FOR FIVE SITES CALCULATED TWO WAYS

Site	Hourly Average Wind Speed (kW)	Simulation Average (kW)	Difference (%)
Kingsley, NB	524	334	-36
Clayton, NB	653	319	-51
Holyoke, MA	610	331	-46
Ludington, MI	827	707	-14
San Gorgonio, CA	[illegible]21	868	+ 6

cut-in but judging from the lower power produced with a 10° maximum yaw error further leads to the belief that the directional variability is quite high. Assuming that is true the machine apparently "chases" the wind while concurrently losing energy. The increase in power shown by free-wheeling over motoring further indicates the wind speed must be in the lower portion of the power curve dipping frequently below cut-out and then right back up. Therefore the power consumed in motoring is not useful but costly. The second site studied, Clayton, NM exhibits some similar attributes to Holyoke, MA as shown in Table 1, Section B. One startling difference is in the apparent number of false starts i.e., the number of times the machine would go all the way through the startup procedure according to the operating strategy but shutdown before any power was produced. Slowing down the low wind speed startup (Table 1, Section C) served to reduce the number of false starts by 11% without however, any appreciable increase in power production. The difference in production between motoring and free-wheeling shows that lulls in wind speed at Clayton are apparently of the order of 4-5 min which is adequate to cause shutdown in the free-wheeling mode but is picked up by motoring and thereby put back on-line with minimum loss. Though this may indicate the size eddies characteristic at Clayton, insufficient investigation into conditions when such eddies occur has been accomplished to call these eddies characteristics. More stringent interpretation of the example results presented here will be found in several forthcoming PNL reports.

SUMMARY AND CONCLUSION

In the limited space available in this forum it is quite difficult to paint a very exact, interpretative picture of the design, development, utilization and results of the use of something like the computer model of the MOD-2 wind turbine. The model was developed in a logical manner and as it was put to more and more use more and more output products evolved. Most of these products have been left out of this report. As of the present our investigation has centered on simple power production and the effects of changes to the production as well as those attributes which may affect the structural dynamics of such a turbine. These results are found in Table 1, Sections B, C, and D and example interpretations found in the Discussion section. The results presented here clearly indicate that site specific, relatively short-term wind characteristics do have an effect on energy production from a MOD-2 wind turbine and the operating strategy can be refined to increase power production without intolerable increases in stress producing maneuvers. Further, though unreported here studies of the modeled operations of a MOD-2 are pointing out the differences and similarities in the larger (synoptic) scale effects on wind characteristics at specific sites such that in the future, armed with a proper understanding of large wind turbine operating characteristics the scientific community can better evaluate expected performance on the basis of hourly data.

ACKNOWLEDGMENTS

This work was supported by the Department of Energy under contract DE-AC06-76RLO 1830.

REFERENCES

1. Miller, A. H. "Implications of the Effects of Wind Characteristics on the Operation of Large Wind Turbines." Proceedings, Intersociety Energy Conversion Engineering Conference, Seattle, Washington. 1980.

2. Meyer, J. W. "Airborne Severe Storm Surveillance. Volume II. Reports of Working Panels, Section II. Report of the Meteorological Panel." Technical Note 1970-43, Vol. II. Lincoln Laboratory, Lexington, Massachusetts. 1971, pp. 83-102.