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SECURITY ASSESSMENT OF POWER SYSTEMS INCLUDING
ENERGY STORAGE AND WITH THE INTEGRATION OF
WIND ENERGY

Progress Report, October 1–December 31, 1979

By
D. P. Carroll
P. C. Krause

January 1980

Work Performed Under Contract No. EC-77-S-02-4206

Energy Sources and Systems Simulation Laboratory
School of Electrical Engineering
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West Lafayette, Indiana

U. S. DEPARTMENT OF ENERGY

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SECURITY ASSESSMENT OF POWER SYSTEMS INCLUDING ENERGY STORAGE
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Progress Report
for Period October 1, 1979 - December 31, 1979

D. P. Carroll and P. C. Krause

Energy Sources and Systems Simulation Laboratory
School of Electrical Engineering
Purdue University
West Lafayette, Indiana 47907

January 1980

Prepared For

THE UNITED STATES DEPARTMENT OF ENERGY
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CONTRACT ACTIVITY

During this quarter, S. Abd El-Hamid (33%), G. E. Gareis (25%), P. C. Krause (17%), C. M. Ong (10%), J. P. Sullivan (5%) and O. Wasynczuk (67%) have been involved in this contract.

INTRODUCTION

The progress of the first three tasks of this contract is reported. At a meeting, chaired by Dr. J. H. Rumbaugh, the program manager, several of the objectives of this contract were modified. The proceedings of this December 4, 1979 meeting at DOE are given in a letter to Mr. Ronald Thomas of NASA from Dr. J. H. Rumbaugh. This letter is Appendix A of this report.

WIND MODELING

The importance of the wind fluctuations upon the performance of any wind turbine generator is not fully understood. The model of the wind selected as the "design model or design gust" effects the design of the wind turbine system, particularly the design of the pitch controller to prevent system instability and the design of voltage regulator or excitation system to prevent voltage flicker. Early in this research the importance of the wind model in influencing the design of the wind turbine generator became apparent. In an effort to encourage DOE to address the problem of wind modeling in the wind characteristics program a position paper was written by Professor Triezenberg and forwarded to Mr. G. P. Tennyson of DOE on July 10, 1979. A copy of this report is given in Appendix B. Therein, the influence of the wind model upon the operation of the MOD-2 in both the high and low modes is clearly demonstrated.

During this quarter two areas have been pursued:

- 1.) Wind turbulence models and their effect on unsteady shaft torque of horizontal machines.
- 2.) Reduced order aerodynamic models of wind machines.

The wind velocity is given by a mean component in the X-direction that varies with height plus a fluctuating component that varied with all three space dimensions and time. That is:

$$\vec{V}_{\text{wind}} = \bar{V}_{\infty}(z)\hat{i}_x + \vec{U}'(x,y,z,t)$$

Note that the mean component $\bar{V}_{\infty}(z)$ contains the mean wind shear. The spatial variations of $\vec{U}'(x,y,z,t)$ play a particularly important role in horizontal axis wind machines since the velocity of the blade is much higher than the wind speed, so the blade sections cut through the spatial variations as if the turbulence was stationary. This model of "frozen" turbulence is being explored for use, especially for the higher frequency fluctuations.

The unsteady shaft torque is found by inserting, $\vec{V}_{\text{wind}}$, into an aerodynamic model of the wind machine. At the present time, a blade element model and a Goldstein model are being explored. Either the unsteady shaft torque can be calculated directly or the average, R.M.S., and spectrum of the torque can be found in terms of various statistical moments of $\vec{U}'$.

The model being developed above will be too complex and require too much computation time to be used in a system simulation. Methods that are used in propeller theory, such as concentrating the aerodynamic loads at three-quarter radius are being considered to reduce the complexity of the aerodynamic model.

MODELING OF SINGLE-UNIT, WIND POWERED GENERATORS

In the meeting with DOE on December 4, 1979 (Appendix A), it was decided to discontinue work on the MOD-1 under this contract. This work is to be replaced with an investigation of the application of variable speed, constant frequency, and discrete speed systems to wind power. In addition, it appears that data for the Shackle machine, now being manufactured by Bendix,

will be delayed for some time.

In accordance with the meeting of December 4, 1979, the problem of resynchronization is to be investigated for the MOD-2 (Appendix A, Item 5). In order to accommodate these and other transient stability studies, the MOD-2 simulation has been modified to include a more accurate representation of the power coefficient. Modifications are still underway so as to include the action of the synchronizer.

Also decided at the December 4, 1979 meeting was the decision to explore variable rotor speed approaches to generating 60 HZ power. The study to be conducted on the computer is to be directed toward solving the problem of resynchronization.

STABILITY INVESTIGATIONS OF SINGLE-UNIT, WIND POWERED GENERATORS

As a result of our studies at NASA/Lewis Research Center and at Purdue, it was discovered that the blade pitch control of the MOD-2 could cause a system instability following a "down gust" in wind. This instability occurred due to a continuous switching between the high and low modes of operation of the pitch controller. According to Boeing this instability has been eliminated by increasing the pitch rate limit from 4 deg/sec to 8 deg/sec. A study was made at Purdue and a report was written and forwarded to Dr. J. H. Rumbaugh. A copy of this report is given in Appendix C. Briefly, the instability with a 4 deg/sec rate limit is demonstrated during a down gust. Next, the performance with a 10 deg/sec rate limit is illustrated. Therein, it is shown that large torques occur on the blades and hub following the down gust even though the system is stable. The possibility of system instability and/or large torques in the gear train due to the pitch control could be a serious problem in operation of the MOD-2.

Another aspect of the MOD-2 is that it represents a class of wind turbine generators of the megawatt size which are to be integrated into power systems in perhaps large numbers to supply a significant amount of power. Common in the present design of this type of wind turbine is the soft, low speed shaft, placed in the mechanical drive train primarily to protect the gears and blades from torque variations originating in the electrical system and to decouple the electrical system from variations in wind torque. Viewed from the blades, this soft shaft appears as a filter to torque variations caused by wind fluctuations. The significance of the soft shaft as viewed from the electrical system came to light in a recent discussion with personnel at Tennessee Valley Authority (TVA). In the case of the MOD-2, the soft shaft twists approximately 3.6° under full load. If, for example, the wind turbine generator is operating under full load and if the feeder line is opened (load rejection) the soft shaft will untwist. The untwisting of this low speed shaft causes the high speed shaft to rotate. With a gear ratio of 100:1, which is common in this class of wind turbines, the high speed shaft will rotate 360° . The generator is a 4-pole machine, hence the rotor angle will rotate 720° , in fact, approximately 1300° in the first transient overswing of the mechanical system. This advance of rotor angle is rapid, occurring in less than one second. Boeing does not recommend reclosing of the transmission line connecting the wind turbine generator to the electrical network. This is to prevent large torque variations on the gears and blades during possible out-of-phase reclosing. Instead, the wind turbine is stalled, restarted and resynchronized. The untwisting of the soft shaft is central to the issue of transient stability. A study of the transient stability of the MOD-2 is being performed. The results of this study will be included in the next quarterly report.

A study of a variable speed wind powered generator is underway. The system being studied concerns a doubly fed induction generator with slip power being fed to the rotor by means of a DC link naturally commutated converter. A first-cut attempt at control of the DC link converters will use conventional HVDC control philosophy. Also underway is an investigation of potential approaches to adjusting the speed of the wind generator by discrete speed changes. A particularly attractive approach concerns a naturally commutated integral cycle cycloconverter. This method is presently undergoing analytical investigation.

APPENDIX A

U.S. Department of Energy
Washington, D.C. 20585

13 DEC 1979

Mr. Ronald L. Thomas
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Dear Ron:

In response to your letter of December 3, 1979 which involved the LeRC grant to Purdue and the Purdue contract with the Division of Electric Energy Systems, I held two individual meetings and one joint meeting on December 4, 1979 to address the LeRC requests.

The first meeting was attended by myself, Dr. Robert J. Thomas of Cornell who is working with me this year while on sabbatical leave, Dr. Thomas W. Reddoch, Mr. Patrick M. Finnegan, and Dr. Leonard J. Gilbert. This meeting was to discuss the LeRC requests based on your current prioritized needs and lasted approximately two hours.

The second group that met excluded the two LeRC representatives and included Dr. Paul C. Krause of Purdue. In this meeting, it was agreed that based upon the LeRC requests, Dr. Krause would perform the following tasks. I note that the time estimates for these tasks are "off the top of the head" projections by Dr. Krause and should not be judged as absolute.

1. Develop a reduced order transient stability model (on the order of two or three cycles) for the Mod-2 machine. Dr. Krause estimates about two calendar months for the completion of a finished product. Since I believe that this analog simulation will consist of two masses, a spring, and a generator; the two month time frame should probably include the validation of this reduced order model against the detailed model Dr. Krause has already simulated. Also this will probably include the use of the wind model described in (2) below.
2. Examine the impact of wind fluctuations on torque control and the gearbox through the new PNL wind model. Mr. Daniel F. Ancona, upon hearing this, suggested a further comparison using the NASA wind model which he considers to be quite similar.
3. Add a detailed Mod-2 model to the two already in existence at Purdue. Dr. Krause feels that he can tie this third detailed model in with the others in a few days.

Mr. Ronald L. Thomas

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13 DEC 1979^{as}

4. Compare the operation of the simulated three detailed Mod-2s with the operation of the three reduced order models using the Goodnoe Hills system to develop a finished three machine reduced order model. This is the first step toward a three machine aggregation and ultimately an aggregate model for a large cluster. Dr. Krause estimates six months for completion of this task.
5. If, as projected, the transient stability problems associated with the Mod 2 are minimal or non-existent; examine the problem of resynchronization using both the complex and reduced order models. Also, on a rudimentary basis, examine system protection schemes.
6. Examine variable speed, constant frequency and voltage configurations. Dr. Lipo is initiating work in this area by looking at:
 - (a) a doubly fed induction machine with a rectifier inverter or a cycle converter;
 - (b) a discrete two speed machine;
 - (c) other variable speed drives.

It was agreed that all simulation work on the Mod-1 would be terminated at Purdue in lieu of item (6) above. Any additional work on the Mod-1 will be handled by LeRC since it is germane to them and probably will not be a production machine.

I look forward to a successful program with a high degree of cooperation. To keep the program on track, I will schedule quarterly review meetings. The first meeting should be held in the approximate time frame of January 15 - February 15, 1980.

Sincerely,

J. H. Rumbaugh
Program Manager
Division of Electric Energy Systems

cc: Dan Ancona
Pat Finnegan
Len Gilbert
Paul Krause
Gerry Park
Tom Reddoch
Bob Thomas

APPENDIX B

July 10, 1979

Mr. G.P. Tennyson
Department of Energy
Wind Systems Branch
Washington, D.C. 20585

Dear Mr. Tennyson:

Enclosed is a short paper written by Dr. D.H. Tricezenberg for the purpose of conveying the need for wind velocity fluctuation data at high sampling rates. For example, at least 2 to 4 seconds in the case of MOD 2. We would welcome the opportunity to discuss this with DOE and/or Battelle personnel. We feel it necessary to inform you of the importance of wind characteristics in the design of wind turbines and their appropriate integration into power systems.

Sincerely,

P. C. Krause
Professor of
Electrical Engineering

cc: L.L. Wendell, Battelle
J.H. Runbaugh, DOE

PCK:ls

The Significance of the Wind Fluctuation Model in
Assessing Wind Turbine Dynamic Performance

D. M. Triezenberg
School of Electrical Engineering
Purdue University
West Lafayette, Indiana 47907

A consideration in the installation of wind turbine generators in conventional electric power networks is the constancy of the power generated. The power flow at any point in a network is not actually constant; it varies as the system load varies. But conventional thermal cycle power generation units are most efficient at constant load. Thus one of the major control considerations in a power system is maintaining voltages and frequency within tolerances while minimizing thermal cycle generator loading changes. If the wind turbines that may be installed in the future do not have a relatively constant output, their presence will make operation of the total power system more difficult to manage, as the power output fluctuations will appear to the thermal cycle generators as increased load fluctuation. Either looser tolerances on network voltage and frequency will have to be accepted or lower efficiency of the thermal cycle units (due to loading changes initiated by control action) will result.

Two factors determine the output power fluctuations of a wind turbine. One is the fluctuations of wind velocity at the turbine and the other is the dynamic electromechanical response of the turbine itself. Of these two factors, the second is probably better understood. Mathematical modeling of electric generators, rotating inertias, and pitch control systems is fairly well developed. It appears, however, that data on wind velocity fluctuations

at a sufficiently high frequency (perhaps 0.1 to 1.0 radian per second) is lacking.

Part of the problem is that the effective wind velocity change over the swept area of the wind turbine blades may not be the same as those seen on the output record of a small anemometer. It is thought that the large blades tend to integrate the smaller localized turbulence centers that would be seen by a small anemometer. This consideration suggests that when a stochastic wind fluctuation model is developed, it should encompass spatial as well as temporal fluctuations. The spatial aspect of the model would be especially helpful in the evaluation of dynamic performance of a windmill "farm".

The NASA/Boeing MOD-2 wind turbine has two basic operating modes. When wind velocity is less than 28 mph, the turbine is unable to develop full output power. Blade pitch is held constant so that output power is maximized. However, for wind velocities above 28 mph, the second operating mode is employed to limit the turbine output to the generator thermal rating. In this mode, blade pitch is continuously adjusted by a proportional-integral controller working off of power error from a full load setpoint. The analog computer simulation reported here represents both operating modes.

Computer studies of the turbine connected to a large power system have been made using two different models for the wind fluctuation. For both models, a discrete interval binary noise (i.e., a signal that switches randomly between two levels) is passed through a simple first order lag low pass filter. The two models differ in the filter time constant, however, for both models the filter gain is adjusted so that standard deviation of the filter output is 2 mph in velocity.

Figure 1 shows the turbine response when the mean wind velocity is 30 mph so that the pitch control system is fully active. In this case the

low pass filter in the wind model cuts off at 0.01 radian per second. The last trace, labeled δ , is the relative angle between the generator rotor and a constant velocity reference. It can be seen that the power fluctuations are a small part of the total output. The full load rating of the MOD-2 generator is 2.5 megawatts. Contrast this with Fig. 2, where the mean wind velocity is 20 mph so that the blades stay at fixed pitch. The absence of pitch control allows the power output to change as much as 0.7 MW in as little as 5 seconds. Such a performance would make the wind turbine an unwelcome addition to a conventional power system. It would be desirable from a control standpoint to use pitch control at outputs less than rated, but this would make wind turbine installation much less economically attractive. Since a large fraction of the total annual output is achieved at wind velocities that are lower than the rating, active pitch control at low wind velocity would reduce this output.

Figures 3 and 4 are a repeat of Figs. 1 and 2, but the low pass filter in the wind fluctuation model now has a cutoff at 0.1 radian per second. The output fluctuations in both operating modes are much greater. Clearly the performance depicted in in Fig. 4 is unacceptable.

On the basis of this study, the investigators of wind turbine system integration can formulate several questions for the investigators of wind characteristics. Which wind fluctuation is more realistic, that of Fig. 1 or that of Fig. 3? If neither is reasonable, then what model is appropriate for the effective wind fluctuation on a single turbine? If two wind turbines are 1000 feet apart, are the individual wind fluctuations correlated?

In summary, it is felt that adequate information on wind characteristics is not presently in the hands of those who must plan wind turbine integration into conventional power systems. It would seem that an appropriate fluctuation model would be a well defined stochastic process.

Fig. 1 - Wind Turbine Response

30 mph mean wind speed

Fluctuation cutoff at 0.01 rad/sec

Fig. 2 - Wind Turbine Response

20 mph mean wind speed

Fluctuation cutoff at 0.01 rad/sec

Fig. 3 - Wind Turbine Response
30 mph mean wind speed
Fluctuation cutoff at 0.1 rad/sec

Fig. 4 - Wind Turbine Response
20 mph mean wind speed
Fluctuation cutoff at 0.1 rad/sec

APPENDIX C

December 11, 1979

Mr. Jeffrey H. Rumbaugh
Division of Electric Engery Systems
Office of Energy Technology
Department of Energy
20 Massachusetts Ave., N.W.
Washington, D.C. 20585

Dear Jeff:

Enclosed is a report entitled "Possible Problems with the MOD-2 Blade Pitch Control." This report describes the problems which may occur in the MOD-2 system as a result of pitch control action during a decrease and subsequent increase in wind velocity. As you may recall I described this to you and NASA on December 3, 1979. After reading the report you may find it appropriate to send copies to Boeing and NASA.

Sincerely,

Paul C. Krause
Professor of
Electrical Engineering

Enclosure

PCK:ls

POSSIBLE PROBLEMS WITH THE
MOD-2 BLADE PITCH CONTROL

P.C. Krause

School of Electrical Engineering
Purdue University
West Lafayette, Indiana 47907

Since November 1978 we have been involved in the analysis and simulation of the MOD-2 wind energy system. Our work began under a NASA grant and is now continuing under a DOE contract. Several reports and papers have been written on the work thusfar [1-6]. During the one year contract with NASA we implemented a hybrid computer simulation of two MOD-2's at NASA/Lewis Research Center and at Purdue. It was discovered that the blade pitch control could cause a system instability following a "down gust" in wind. In particular, if the system were initially operating in a wind velocity of slightly above 28 mph so that the blade pitch control is in the high mode and if a down gust occurred causing the blade pitch control to switch to the low mode and then back to the high mode, an instability could occur resulting from continuous switching between the two modes. This was demonstrated to Boeing by NASA at which time it was also pointed out that an increase in the rate limit of the pitch control would prevent the instability. Hence the rate limit has been increased from approximately 4 deg/sec to 8 deg/sec.

Figures 1 and 2 show the behavior of the MOD-2 during a down gust of 1-cosine waveform from 30 mph to 20 mph and back to 30 mph in 10 sec. Figure 1 illustrates the sustained oscillation which occurs with a rate limit of 4 deg/sec. On the NASA simulation an oscillation, increasing in amplitude,

was noted for slightly different operating conditions. Figure 2 shows the behavior of the MOD-2 with a rate limit of 10 deg/sec. In each figure the following system variables are plotted.

T_{W1} = per unit wind torque on blade 1 (each blade is represented as a lumped mass).

$\Delta\omega_{B1}$ = per cent change in the speed of blade 1.

T_{BH} = per unit torque transmitted from blades to hub.

V_T = per unit magnitude of the terminal voltage.

β = blade pitch angle in deg.

$\Delta\omega_G$ = per cent change in generator speed.

δ = rotor angle in electrical deg.

T_e = per unit electromagnetic generator torque.

Changing the rate limit from 4 to 10 deg/sec eliminated the unstable conditions, however, the large torque on the blades and gears as well as the variation in terminal voltage during the down gust with the 10 deg/sec rate limit (Figure 2) are of concern. In this mode of operation the soft shaft is not protecting the blades and gears from large torque variations.

Since it is difficult for us to obtain the up-to-date design of the blade pitch control our representation may not portray the present operation of this control system. Regardless of possible inaccuracies, it is recommended that NASA and Boeing be made aware of these results by means of a copy of this report.

1. D.M. Triezenberg, "Wind Turbine-Generator Simulation Seminar," (Written Report), May 1979.
2. M.G. Reynolds, "Stability of Wind Turbine Generators to Wind Gusts," Purdue University Technical Report, TR-EE 79-20, May 1979.
3. L.J. Gilbert and D.M. Triezenberg, Lewis Research Center, "Studies of Multiple Large Wind Turbine Generators on a Utility Network," Workshop on Economic and Operational Requirements and Status of Large Scale Wind Systems, Monterey, California, March 28-30, 1979.

4. L.J. Gilbert and D.M. Trlezenberg, "Simulation Studies of Multiple Large Wind Turbine Generators on a Utility Network," Workshops on Large Wind Turbine Design Characteristics and R and D Requirements, Cleveland, Ohio, April 24-26, 1979.
5. D.M. Trlezenberg, "The Significance of the Wind Fluctuation Model in Assessing Wind Turbine Dynamic Performance," a position paper, July 1979.
6. P.C. Krause, "Analysis and Simulation of Wind Energy Systems," Final Report for NASA (in draft form), November 1979.

P.C. Krause
December 12, 1979

Fig. 1. Ten MPH Down Gust with 4 deg/sec. Rate Limit in Pitch Controller.

Fig. 2. Ten MPH Down Gust with 10 deg/sec. Rate Limit In Pitch Controller.