SIMULATION STUDIES OF MULTIPLE LARGE WIND TURBINE GENERATORS ON A UTILITY NETWORK

Leonard J. Gilbert
NASA Lewis Research Center
Cleveland, Ohio 44135

and

David M. Triezenberg
Purdue University
West Lafayette, Indiana 47907

SUMMARY

The Wind Energy Project Office of NASA-Lewis has undertaken, as part of the Department of Energy wind program, a multi-faceted project to study the anticipated performance of a cluster of wind turbine generators on an electric utility network. Both in-house and contractor resources are being used. Preliminary results of an in-house simulation of two Mod-2 systems tied to an infinite bus indicate favorable system performance.

INTRODUCTION

With the impending construction in 1980 of three Mod-2, 2.5 Megawatt, wind turbine generator systems, the necessity to identify any potential problems inherent in the operation of a cluster of such machines on a utility network becomes critical. The nature of wind turbine torque and drive train characteristics coupled to the variability of the wind excitation is such as to produce a generating system that warrants special analyses to assure its compatibility with established electric utility networks. In accordance with this requirement, the Lewis Research Center of NASA, as part of the DOE wind program, has established a project to investigate the interaction between a cluster of large wind turbine generators and a utility network.

The effectiveness of a single large wind turbine generator (WTG) synchronized to an electric utility network has been demonstrated by the Mod-OA, 200 kw, wind turbine generators operating at Clayton, New Mexico and Culebra, Puerto Rico, and the 100 kw, Mod-0 generator at the Plum Brook Station of the Lewis Research Center. The analyses of these machines on their networks have been reported by Seidel (Ref. 1), Reddoch and Klein (Ref. 2), and Power Technologies, Incorporated (Ref. 3).

Although concern for the possibility of interaction problems between wind turbine generators and a network has been expressed in the past, few results of studies of this interaction have been published. Pantalone and Fouad (Ref. 4) have studied multi-unit operating point stability with a constant wind excitation, a parametric eigenvalue analysis.

The General Electric Company performed a study for ERDA (Ref. 5) which initiated an investigation into the interface design requirement for large scale application of wind turbine generators. Currently the Division of Electric Energy Systems of the Department of Energy is sponsoring a study of the dynamics of multi-unit wind turbine generators on electric utility systems. This study is being performed by Power Technologies, Incorporated and is scheduled to be completed by January 1980.

The intent of this paper is to describe the approach of the Lewis Wind Energy Project Office to developing analysis capabilities in the area of wind turbine generator-utility network computer simulations and to present some preliminary results of an analog simulations study of multiple-unit wind turbine generators tied to a utility network.

MOD-2 SIMULATION

The simulation model of the Mod-2 wind turbine generator that has been modeled in the hybrid computer laboratory at the Lewis Research Center is shown in Figure 1. The Mod-2 is a horizontal axis system with a two-bladed, upwind rotor driving a 2.5 Megawatt synchronous generator. Among the distinctive features of the system are the low-speed quill shaft designed to reduce torque oscillations by virtue of its relatively high compliance, and a two-per-revolution notch filter in the actuator command signal path to relieve the actuator from cycling at that frequency. The effects of both of these features are apparent in the simulation output signals.

The objective of this paper is to demonstrate the nature and application of the simulation. Detailed parameter values are not included here other than to indicate that they were obtained from the Boeing Company. Implementation of the simulation was completed in February and only limited studies of the type illustrated here have been performed. The data used was that included in the "Mod-2-107 Preliminary Design Blade Pitch Control System Simulation Report" by the Boeing Company, dated February 27, 1979. As the final design proceeds and parameter values are better defined, the simulation will be modified to reflect the latest available parameter values.

<u>Analog Simulation of a Two-Wind Turbine System</u>. - The simulation of two Mod-2 wind turbines, radially connected to an infinite bus, was implemented through a joint effort of Puedue University and NASA-Lewis. The common radial connection of the two generators provides an electrical interaction between them.

It was determined at the outset that representation of electromagnetic transients in the radial transmission line and in the machine stators would not be required, since such transients are not important to electromechanical motion. Thus, the electrical representation of each generator involves three state variables, namely field flux linkage and damper flux linkage in the q and d axes. Use of flux linkages as state variables allows a convenient and physically reasonable representation of saturation.

Torsionally-induced motion of the system is represented by three rotational inertias (1. blades, 2. hub and quill shaft, 3. gearbox and generator) connected by elastic shafts. Six state variables are involved: three speeds, two shaft torques, and the displacement between the generator inertia and a constant angular velocity reference.

A brushless exciter produces field current for the generator. Simulation of this component is done with only one state variable (exciter field flux), plus several algebraic relations to describe the action of the rotating rectifier. The static voltage regulator model adds three more state variables.

The simulation of aerodynamic effects is done by algebraic equations. Wind torque is proportional to a power coefficient and to the cube of the wind velocity, and is inversely proportional to rotational speed. Curve fitting is used to represent the power coefficient as a function of tip speed ratio and pitch angle.

The pitch control subsystem in the simulation is that designed by Boeing. It uses four state variables: one in an integral controller, one for the hydraulic servo, and two for a "2P" notch filter. In all, seventeen state variables are employed in each wind turbine model.

The equations and integrations required for one wind turbine are implemented on an EAI 681 analog computer. Simulation speed is real time or ten times slower than real time. Two EAI 681 consoles are operated in parallel to implement the two wind turbine system. The simulation is in real time and interactive. Repeated runs with parameter changes are quickly accomplished.

Comparison with Boeing Simulation Results. - The first response examined the response of a single wind turbine generator, rigidly tied to an infinite bus, to a (1-cos) gust. This response was examined to compare with results obtained by the Boeing Company, the designer of the Mod-2 system, with its digital simulation of a single machine (Ref. 6). The results of the two simulations matched closely. The comparison figures are included in Figure 2. The steady-state wind speed was 28 mph. Upon this was superimposed a 30-second (1-cos) gust which produced a peak speed of 1.41 times the steady-state speed. As a result of the 41% gust, each model indicated ±8% variation in electromagnetic torque and a pitch angle change of 10.5 degrees. The NASA model showed a power angle change of ±2 degrees; the Boeing model, ±1.5 degrees.

Gust Response of Two Machine Model. - The simulation was developed for two identical Mod-2 wind turbine generators. The two systems were coupled to an infinite bus through a reactive line as depicted in Figure 3.

The two coupled systems, each operating in a 28 mph steady wind, were subjected to a 13.8 second, 28% increase in wind speed, (1-cos) gust. This gust has been designated the "Design Gust" for the Mod-2 wind turbine generators (Ref. 5). The response of each system to gusts at two different time relationships between the gusts is shown in Figures 4 and 5. The transmission line reactance was a relatively high 0.4 p.u.

Figure 4 shows the response of the two machines to a gust on machine #1 only. There is about a ±8% change in rotor torque for machine #1, but the only change observed in machine #2 is a ±1 degree change in the power angle.

In Figure 5 responses are shown for both systems subjected to the same gust, but machine #2 experiences the gust about 7 seconds after machine #1 does. No interaction is observable and each system appears to respond as it would without the presence of the other.

For the two sets of gust responses illustrated, the system is stable. There is little, if any, interaction of the quantities monitored for the particular operating point and configuration of generators modeled.

One WTG Tripped Off Line. - A case was run simulating the response of WTG #2 when WTG #1, which had been operating in parallel with WTG #2, dropped off the line. Both machines had been operating at rated load in a 28 mph wind, connected to an infinite bus through a 0.4 per unit reactive line. The resulting transient on WTG #2 lasts about 2 seconds, decaying rapidly. The machine remains synchronized and the output power returns to the rated value. This response is illustrated in Figure 6. It is pertinent to note that the model at this stage included no rate limit on the control blade pitching. Future simulation runs will include a rate limit and may produce different results.

Fault at WTG Bus. - With the two machines operating in parallel in a 28 mph wind and each generating rated power, a .04 second three-phase short circuit was applied at the common WTG bus. A local load of 2 per unit was also tied to the system at the WTG bus. The WTG bus was connected to the infinite bus through a 0.4 per unit reactive line. The results of this simulation is shown in Figure 7. The signal traces for only one machine are shown. The second machine traces are identical. The machines quickly recover from the effect of the fault when the portion of the network including the fault is removed. After a half-dozen swings, the transient has disappeared and the system has returned to its original condition.

Effect of Actuator Time Constant. - In order to observe the effect of doubling the time constant of the blade pitch actuators simulations of faults on the parallel WTG's were compared using the nominal time constant and a time constant of twice nominal value. The results are shown in Figure 8. With the two WTG's operating at rated load in a 28 mph wind a 0.02 sec three-phase short circuit occurs at the WTG bus. In each case, when the fault is cleared, the systems return to the pre-fault operating condition. (Traces of only one machine are shown.) Close inspection of the traces show the effect of the longer time constant. However, the effects are very small, and considerable variation of the time constant parameter appears to be possible.

CONCLUDING REMARKS

The Lewis Research Center Wind Energy Project Office has undertaken a multi-faceted investigation of potential electrical problems that may be inherent in the intertie of clusters of wind turbine generators and an electric utility network.

Preliminary and limited results of the analog simulation study of two Mod-2 wind turbine generators tied to an infinite bus indicate little interaction between the generators and between the generators and the bus. The system demonstrated transient stability for the conditions examined.

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DISCUSSION

Q. Serious problems usually occur as a result of more than one fault happening simultaneously. Are you planning to look into two or three things happening at the same time?

A. Yes. These results were obtained last week, so they are preliminary. There are many, many things to study, and the ones you suggest certainly are pertinent.

Q. You have said that the inertia constant is high. What is the inertia constant for the Mod-2?

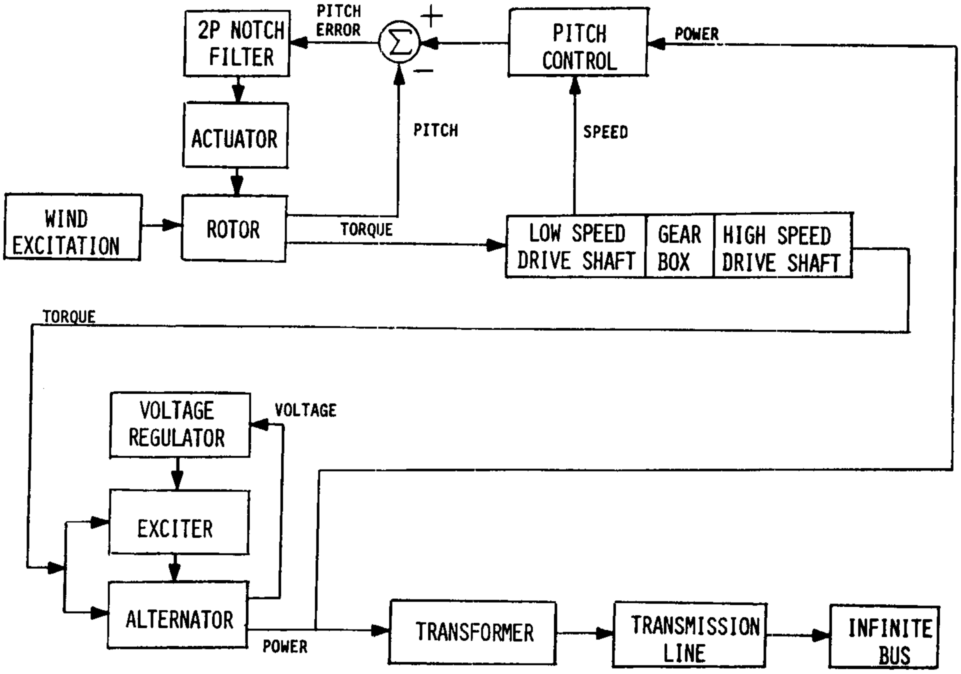
A. It is 16.5 kilowatt seconds per kva.

Q. You mentioned that the control system was very rapid. What was your time constant?

A. I believe the time constant is one-sixth of a second.

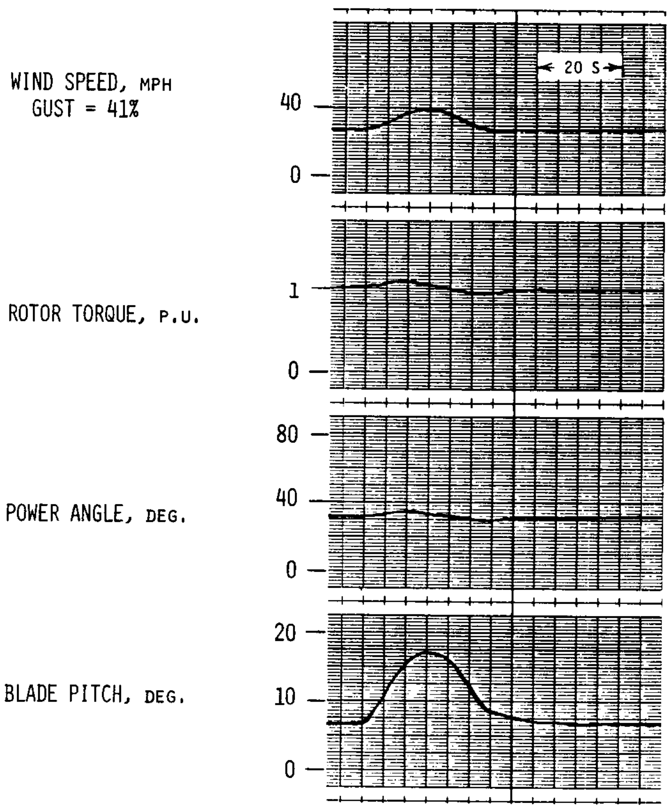
Q. I wasn't sure exactly what was covered in the Power Technologies study. When are the results going to be available? Secondly, General Electric did make a study of power group stability. Are you familiar with that report, and do you know what it contains? Is it available yet?

A. The General Electric study is not available. I think it is fair to say that it is not an extensive study. It was really an introduction to the problem, and GE ran out of time before really getting into the problem. Power Technologies Incorporated started with a one-year study for the Department of Energy in December of 1978. It is going to look at a single machine on a network and then two machines on a network. The parameter changes principally are going to be in the size of the machine, whether it is 200 kw or three megawatt, to see if there is a connection between size and performance. They are also going to look at the same kind of thing that I looked at.



MOD-2 SIMULATION BLOCK DIAGRAM

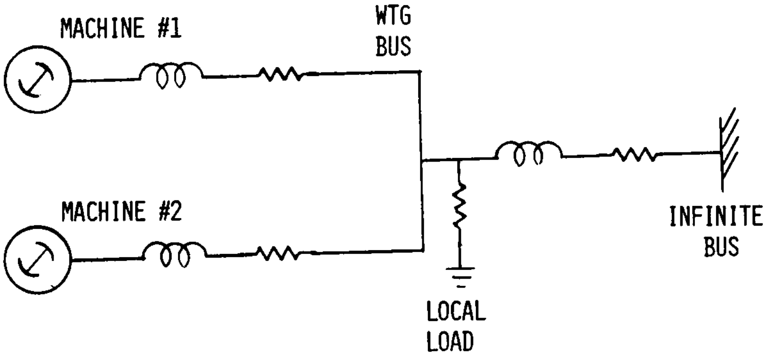
FIGURE 1



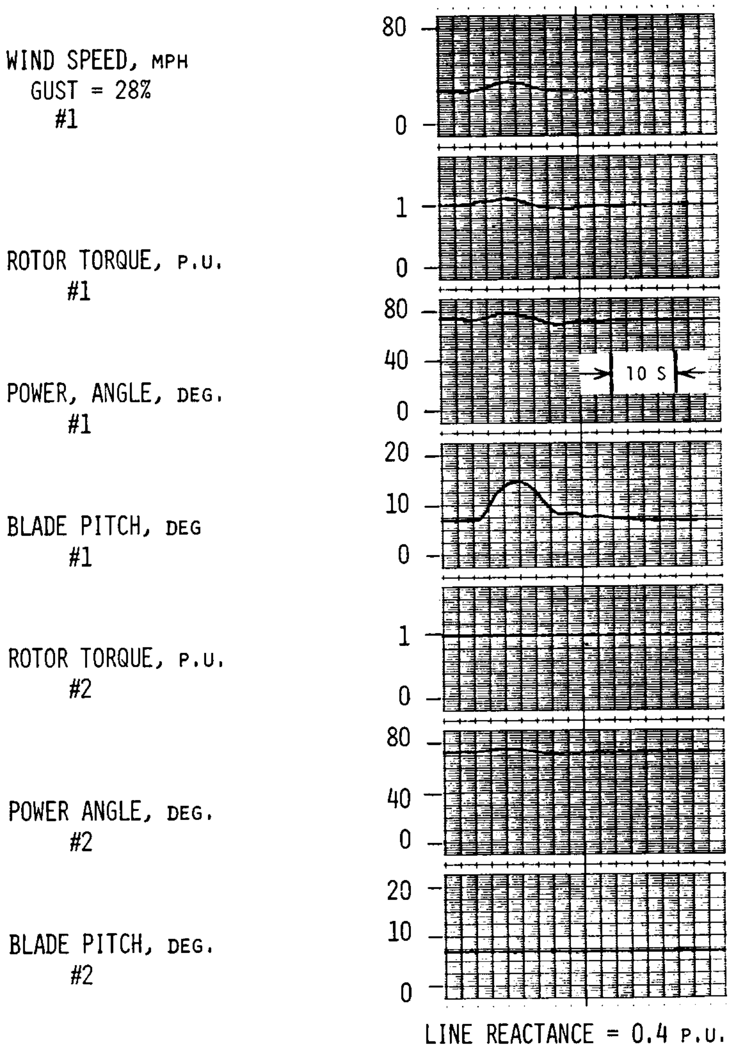
SINGLE MOD-2 LOAD GUST RESPONSE

28 MPH + 41%, 30 SEC GUST

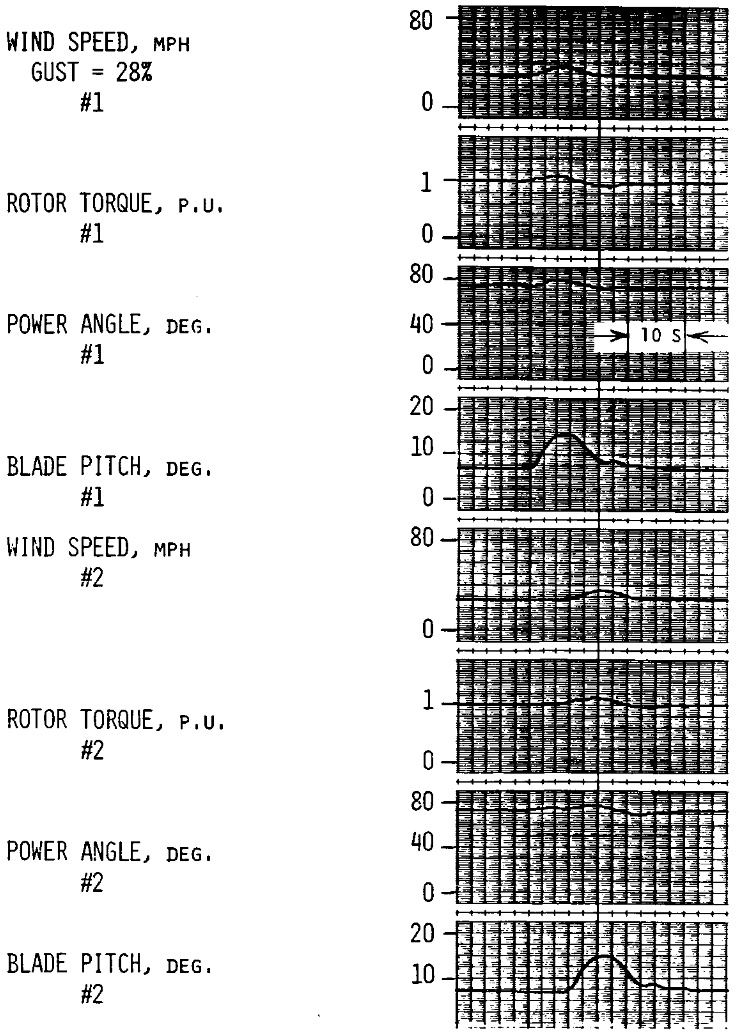
FIGURE 2



TWO WIND TURBINE GENERATORS ON AN INIFINITE BUS
FIGURE 3

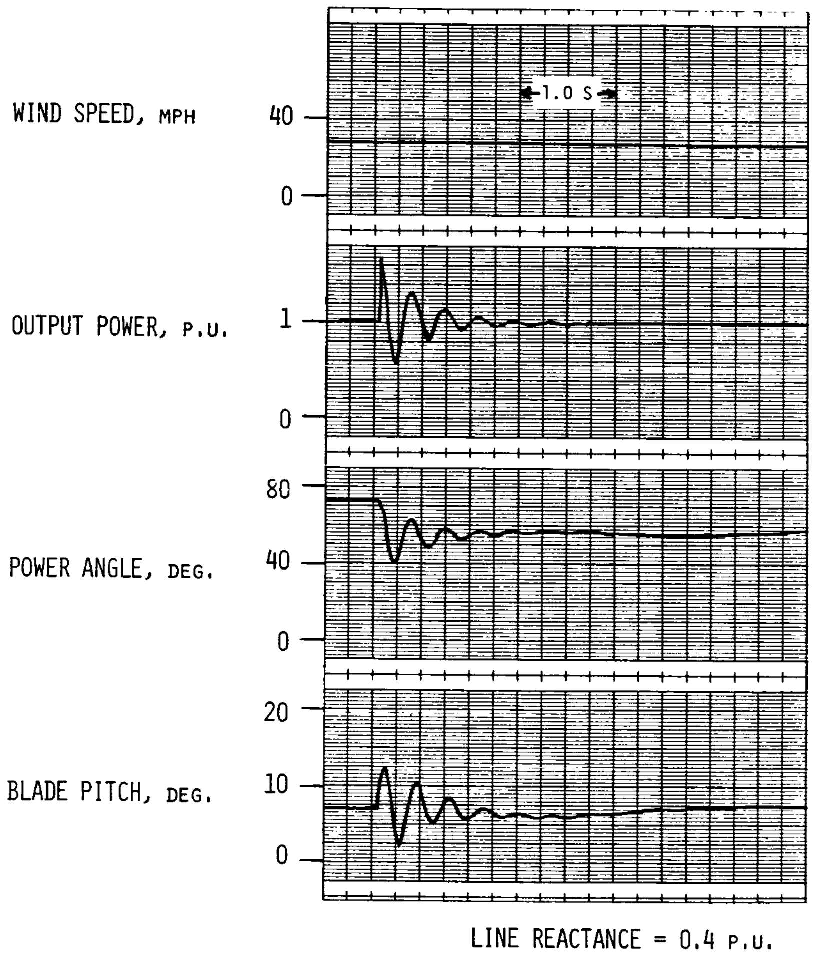


TWO WIND TURBINE RESPONSE
GUST HITS #1
FIGURE 4



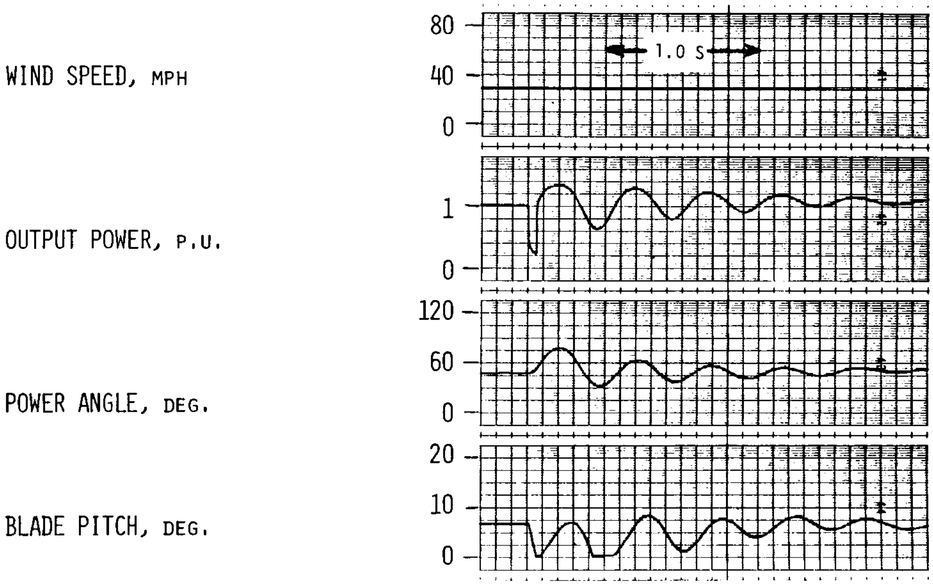
TWO WIND TURBINE RESPONSE
GUST HITS #1 AND #2

FIGURE 5



RESPONSE OF WTG #2
WHEN WTG #1 IS TRIPPED OFF LINE

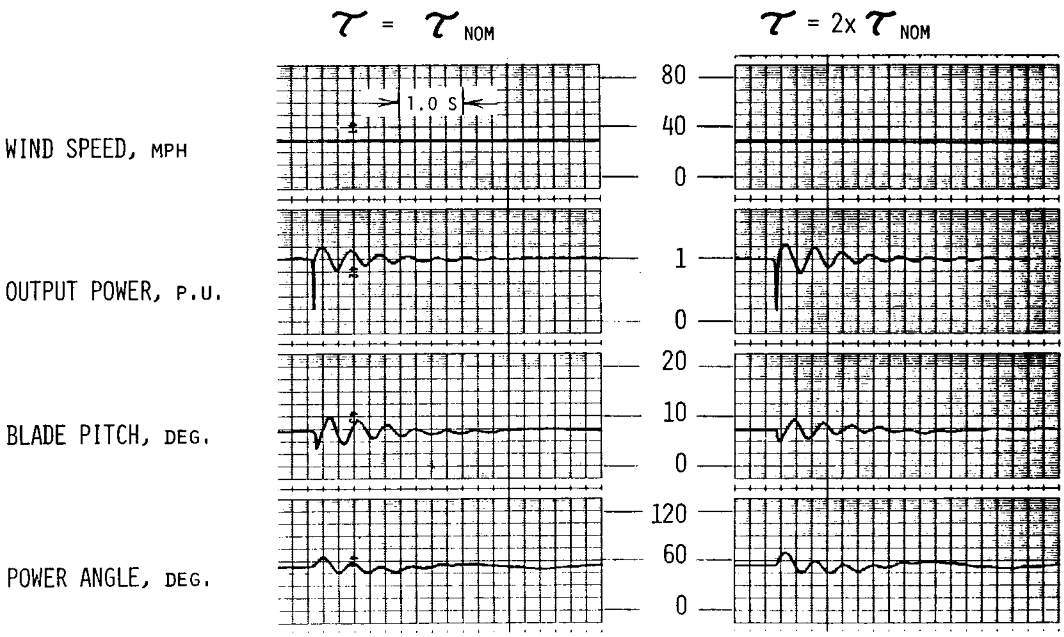
FIGURE 6



LINE REACTANCE = 0.4 P.U.

PARALLELED WIND TURBINE GENERATORS ON A NETWORK
.04 SECOND FAULT AT WTG BUS WITH LOCAL LOAD = 2 P.U.

FIGURE 7



LINE REACTANCE = 0.4 P.U.

PARALLELED WIND TURBINE GENERATORS ON A NETWORK
.02 SECOND FAULT AT WTG BUS
ACTUATOR TIME CONSTANT τ VARIED

FIGURE 8