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INVESTIGATION OF EXCITATION CONTROL FOR WIND-TURBINE GENERATOR STABILITY

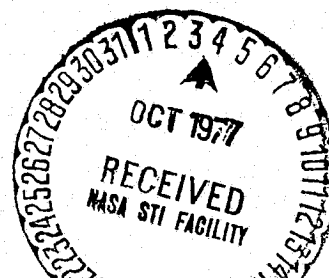
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16. Abstract High-speed horizontal-axis wind-turbine generators with blades on the downwind side of the support tower require special design considerations to handle disturbances introduced by the flow wake behind the tower. Experiments and analytical analyses were made to determine benefits that might be obtained by using the generator exciter to provide system damping for reducing power fluctuations. Excitation control was not a suitable solution for the NASA-Lewis Mod-0 Wind-Turbine Generator.					
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INVESTIGATION OF EXCITATION CONTROL FOR

WIND-TURBINE GENERATOR STABILITY

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INTRODUCTION

High-speed horizontal-axis two-bladed wind-turbine generators (WTG) with blades on the downwind side of the support tower are being developed by NASA/ERDA. This design has advantages of high aerodynamic efficiency, high output power, and using materials efficiently. It does, however, require special design considerations to handle disturbances introduced by the flow wake behind the tower. Aerodynamic forces that change as the blades travel through the wake can result in high mechanical stresses and electrical power fluctuations. The problem has been noted in the literature (ref. 1) and observed during certain operating conditions of the NASA-Lewis Mod-0 WTG.

Several schemes for adding damping to the drive train system and/or reducing the bandwidth of the drive train system in order to suppress the effects of input torque disturbances have been proposed. This report investigates the possibility of adding damping to the system by controlling the generator exciter. Effective damping will result if torque can be applied to the generator rotor with a phase relationship such that the torque opposes changes in the generator's power angle. Because the effective time constants are small in excitation control loops, it was assumed that a large control effort could be expended with relatively small input of control energy (ref. 2). This technique was encouraged by successes obtained in the 1960s that improved power system stability of large utility networks.

Experiments and analyses of the NASA Mod-0 WTG system have been made to determine benefits that might be obtained by using the generator exciter to provide system damping. The analyses are discussed first, and then test results are given.

ANALYTICAL MODEL

A linear mathematical model provides information for predicting the effectiveness of using excitation control for suppressing power oscillations caused by the flow wake behind the WTG tower. Linearization is obtained by operating in a small neighborhood about equilibrium points. With this approach the input torque (driving function) to the system is expressed as

$$T = T_0 + T^*$$

where T_0 is an equilibrium point and T^* is an incremental component that represents the disturbance generated by the flow wake. Figure 1a shows the resultant small-signal model of principal dynamics of the WTG drive train system.

The drive train portion of the system is described by a second-order circuit. The inertia element (element 1) includes the blades, hub, gears, and brake inertias. The spring element (element 2) combines the compliances of low speed shaft, coupler, gears, high speed shaft, belts, and generator shaft. Wind drag and bearing frictions are lumped together as a single damping parameter (element 3). Element TF increases shaft speed without loss of energy. Propeller speed is 27 RPM and generator speed is 1800 RPM.

The generator portion is modeled by a second-order system. The generator rotor (element 4) has four torques applied to it; mechanical torque from element 2, field spring (element 5), generator damping (element 6), and compensation torque produced by the exciter (element EXC). Small changes in electrical output power are approximated by

$$P^* = Af^* + B\delta^*$$

where A is a constant, f^* represents the incremental component of torque induced by the exciter field, B is a constant, and δ^* is the incremental component of generator power angle. This linear expression for output power represents characteristics corresponding to small excursions at a typical equilibrium point on the Power/Angle plot sketched in figure 1b.

System analysis is divided into two parts. The first evaluates the maximum damping effects that the exciter can apply to the first-mode resonance. The second part is used to predict the output characteristics expected from the frequency response test on the Mod-0 WTG.

To determine the best improvements that can be expected for the drive train system, an ideal exciter is assumed. Torque f^* applied to the rotor by the ideal exciter is defined as being proportional to exciter current i^* and independent of frequency. In addition, if i^* is proportional to δ^* then the compensation torque will directly oppose changes in power angle. Results for this modeling situation are shown in figure 2 for three different AMPL GAINS.

Figure 2 presents frequency response Bode plots of the electrical output power per input torque. These Bode plots have the gain scale on the y-axis normalized by assigning 0 DB at zero frequency. Frequency on the x-axis has units of radians/second.

The frequency response of the uncompensated drive train (AMPL GAIN = 0) is shown in figure 2a. The first resonant mode is the main concern because its frequency is near the 5.655 rad/sec (0.9 Hz) driving frequency produced by the

blades passing through the tower wake for a hub speed of 27 RPM. The high gain (32 DB) at the first mode results from having damping coefficients lower than expected in the real system. Low damping was intentionally used in this part of the analysis to highlight the improvements that might be obtained with excitation control. The damping ratio with respect to elements 1, 2, and 3 is 0.003 and a damping ratio of 0.01 is assumed for the basic generator (elements 4, 5, and 6).

Increases in AMPL GAIN reduce first-mode amplification factor, as expected, until a minimum of 9.7 DB (ratio = 3.1) is reached at an AMPL GAIN of 400. This minimum was interpolated from frequency response analyses of several different AMPL GAINS not presented in this report. Results are displayed in figure 2b. Second-mode resonance is absent in this optimal gain condition.

Further increases in AMPL GAIN then increase first-mode amplification factor toward the dynamic characteristics of the drive train only; i.e., with element 4 held rigid. For example, a high AMPL GAIN of 10000 increases the first-mode amplification factor to 33 DB (45). The outcome is shown in figure 2c.

Exciter current required for these cases can be determined by computing the frequency response between the wind input torque and exciter current. Results for the optimal case (figure 2b) are shown in figure 3. The y-axis is normalized such that 0 DB is defined by the ratio of rated exciter current (2.8 amps) per rated wind input torque (100 kW). The 6.6 DB gain at 5.655 rad/sec means that an amplitude of 100 percent rated exciter current occurs when the input torque amplitude is 47.6 percent of its rated value. This frequency response characteristic is barely suitable because higher exciter currents would be needed in the real system to compensate for exciter dynamics neglected in the model.

The three Bode plots in figure 2 clearly illustrate that the exciter primarily affects the second-mode resonance and that the optimal control of exciter torque provides but very little damping to the first mode.

The second part of the analysis evaluates the dynamics expected in the test data. The parameters of the model were changed to make the frequency response more closely correspond to the real system. Figure 4 shows the frequency response of the model configuration used to represent the real system. It was obtained with parameter 3 increased by a factor of 20, and parameter 6 by a factor of 5. With these values the model still has a first resonant mode near the blade-to-tower driving frequency but with amplification reduced by a factor of 10 (from 31.7 to 11.8 DB). The second mode is essentially eliminated by the additional damping.

Figure 5 shows the open loop frequency response of the electric output power as a function of exciter current. The

scale representing amplitude ratio in figure 5 is normalized such that 0 DB is defined by the ratio of rated power (100 kW) per rated exciter current (2.8 amps). Frequency response of torque f^* as a function of current i^* was assumed to be equivalent to the frequency response of reactive power which for the Mod-0 generator could be represented by a second order linear low-pass filter with cutoff at 10.7 rad/sec (1.7 Hz).

Response plot of figure 5 discloses a narrow bandpass with output power being affected only over the frequency range between 4 and 9 rad/sec (.6 to 1.4 Hz) where the ratio of rated output power to rated exciter current is greater than -6 DB (0.5). A maximum amplification ratio of 4.4 DB (1.7) is evident at 5.5 rad/sec (.87 Hz).

Conclusion drawn from figure 5 is that useful data from excitation control tests will be limited to a narrow frequency range coincident with the first resonant mode. Outside of this range the effects of exciter current will be undiscernible, particularly in the presence of the high output power fluctuations normally produced by the flow wake behind the tower. This conclusion is supported by the test described in the next section.

MOD-0 WTG TESTS

The purpose was to experimentally determine if exciter current can produce sufficient torque to suppress power oscillations. The approach was to observe frequency response characteristics of the system with the WTG synchronized to the grid. The input signal was a large amplitude sinusoidal exciter current of 40% rated (80% peak-to-peak rated) and the recorded outputs were low speed shaft torque, electrical power, and reactive power. The turbine speed was 20 RPM instead of 27 used in the analysis.

Quiescent conditions to be tolerated in the tests are obtained by observing the output signals during constant current input to the exciter. These are displayed in figure 6. The time scale is 10 seconds per minor division. The torque signal was not calibrated and was intended for use only as an indicator. The scale for electric power is 30 kW per major division; reactive power is 40 kVAR per major division. The setpoint for power was 40 kW. Power peaks went as low as zero and as high as 80 kW. The high frequency portion of the signal is the blade-to-tower frequency (0.67 Hz). Reactive power had an average value of approximately 20 kVAR and also displayed the 0.67 Hz oscillation. This oscillation being superimposed on the frequency response data greatly encumbered the data reduction.

A frequency sweep of exciter current was conducted between 1.25 and 63 rad/sec (.2 to 10 Hz). No changes in the power or torque could be observed in the recordings.

Reactive power followed very well.

A different approach to the test procedure was taken to overcome the noise hinderance shown in figure 6. The new test was based on the following proposition. If the generator exciter is capable of applying torque to the rotor and if it can be used to suppress the blade-to-tower frequency disturbance, then a beat frequency in the torque and power signals should be detectable when the blade-to-tower frequency and the exciter current frequency are almost equal. This concept is shown pictorially in figure 7 where $2P$ represents the blade-to-tower frequency and $\Delta 2P$ is the beat frequency.

The test was conducted by using a beat-frequency period of 350 seconds. The results are shown in figure 8 where the time scale is compressed to 100 seconds per minor division. The diamond symbols were added to the recording to show the 350-second beat-frequency period. Their location relative to the time scale was selected in an attempt to accent the beat pattern in the torque signal. Figure 9 is a recording with the same time scale as figure 6 and shows one beat-frequency period.

Comparison of figures 6, 8, and 9 discloses that the torque applied by the Mod-0 exciter is very weak. In contrast, the exciter increased the reactive power oscillation to an amplitude of 60 kVAR (120 kVAR peak-to-peak). The combination of low torque reaction and large excursions in reactive power indicates that the exciter is not a suitable device for adding damping to the drive train system of the Mod-0 WTG.

CONCLUSIONS

Two conclusions were obtained from the investigation. The mathematical analysis disclosed that the first-mode amplification factor (first resonance) of the Mod-0 WTG can be reduced but not eliminated by adding damping to the generator. Secondly, it was clearly demonstrated by response tests that any advantages for excitation control to obtain improvement in system dynamics would be completely cancelled by the accompanying excursions in reactive power. Thus it was determined that excitation control is not a suitable method for suppressing Mod-0 WTG power oscillations caused by the flow wake behind the tower.

REFERENCES

1. Johnson, Craig C.; and Smith, Richard T.: Dynamics of Wind Generators on Electric Utility Networks. IEEE Trans. Aerosp. Electron. Syst. vol. AES-12, no. 4, July 1976, pp. 483-493.
2. Anderson, P. M.; and Fouad, A. A.: Power System Control and Stability, Iowa State Univ. Press, 1977.

PARAMETER	VALUE
1	$1 \times 10^5 \text{ ft lb sec}^2$
2	$6 \times 10^6 \text{ ft lb/rad}$
3	$4834. \text{ ft lb sec/rad}$
4	$0.7156 \text{ ft lb sec}^2$
5	$1388. \text{ ft lb/rad}$
6	$8.84 \text{ ft lb sec/rad}$
TF	66.67 RPM/RPM

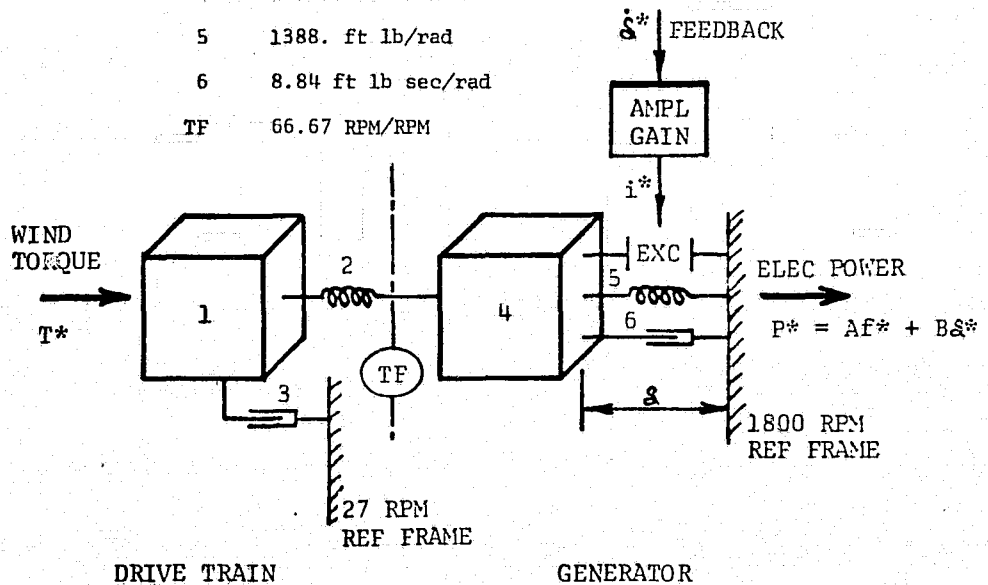


Figure 1a. - Analytical small-signal model of drive train system dynamics.

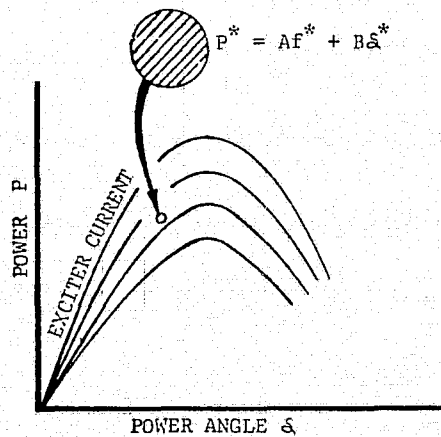


Figure 1b. - Typical Power/Angle characteristics of synchronous generator.

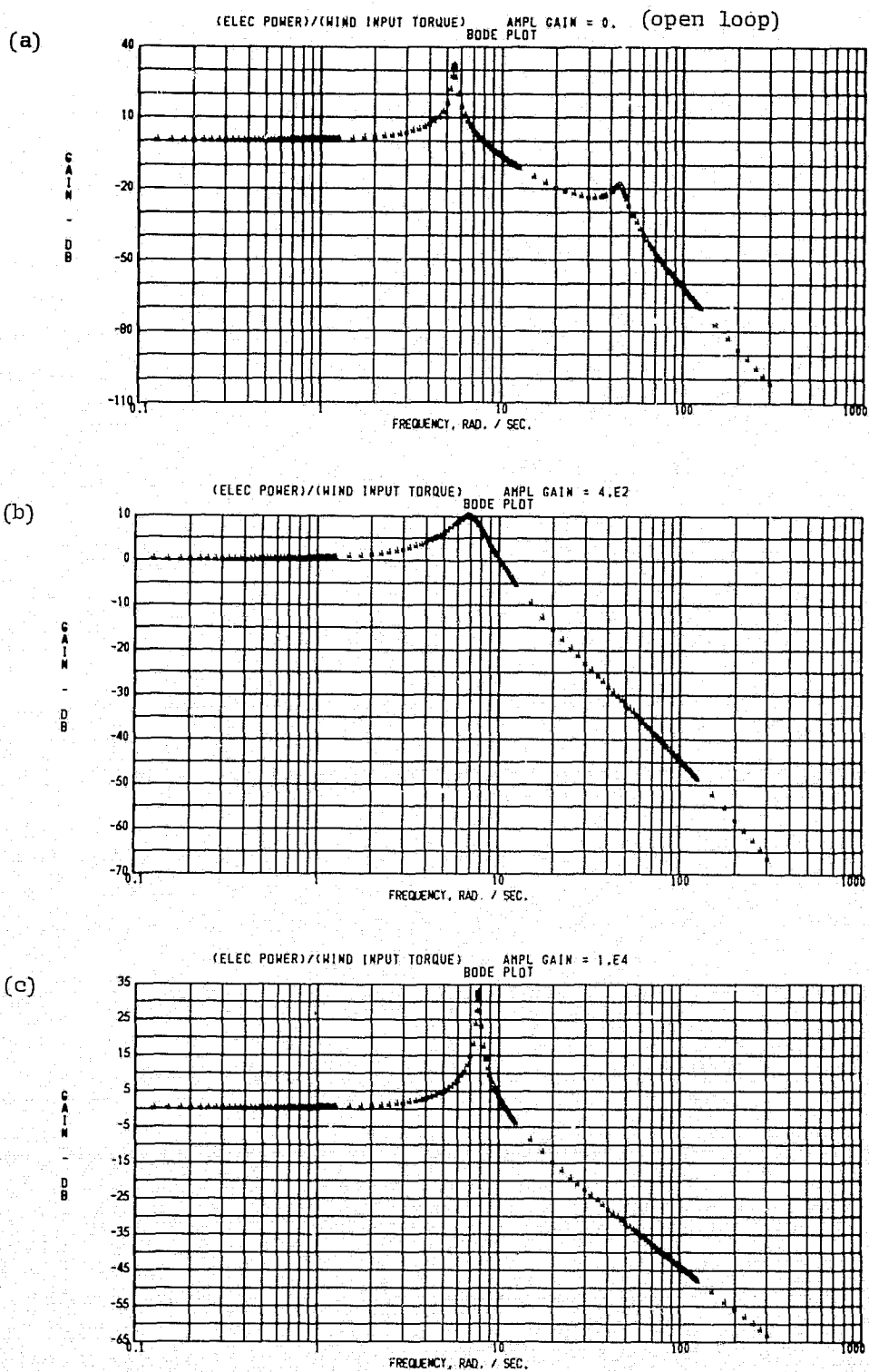


Figure 2. - Frequency response of model in figure 1a.

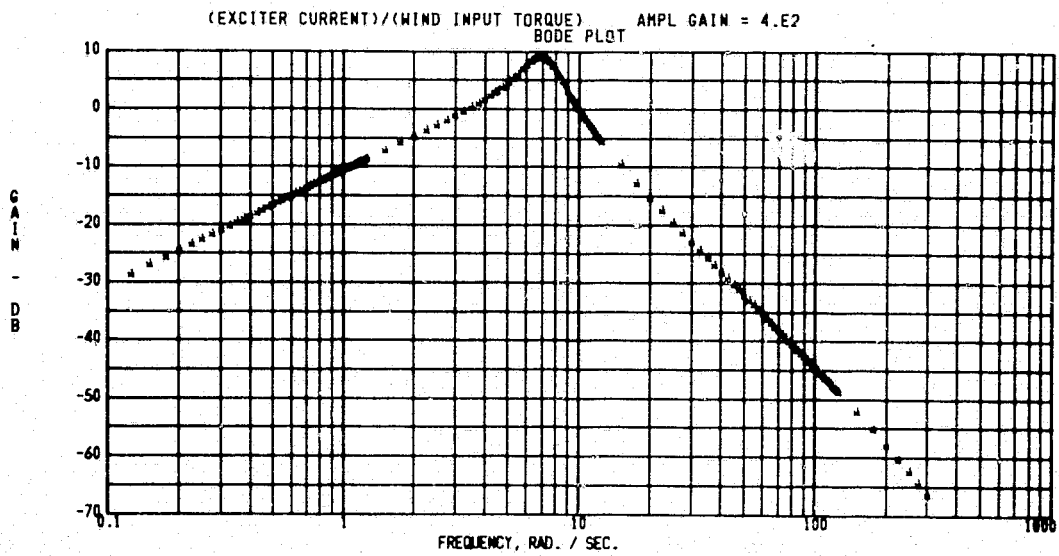


Figure 3. - Exciter current for optimal case in figure 2b.

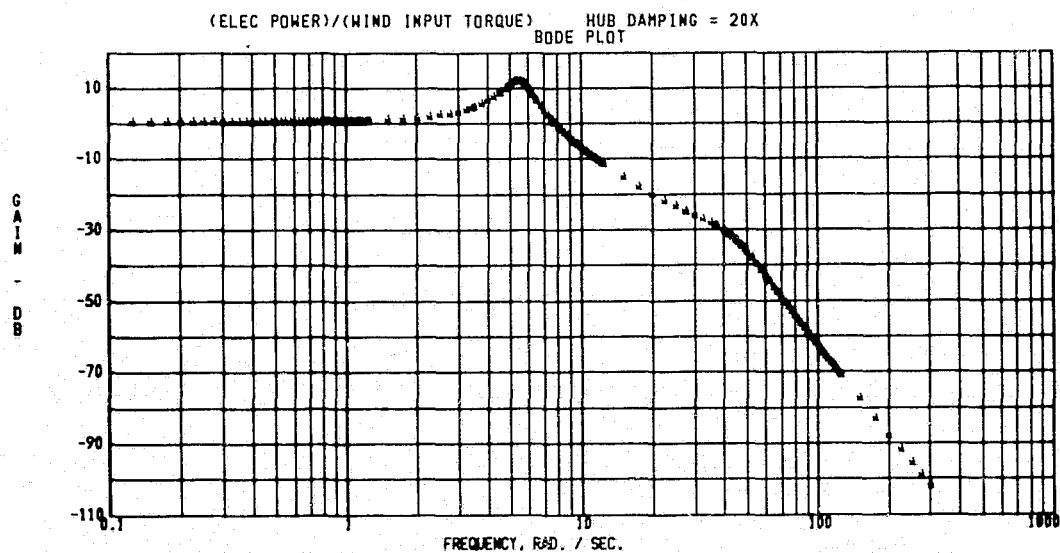


Figure 4. - Frequency response of model in figure 1 but with increased damping.

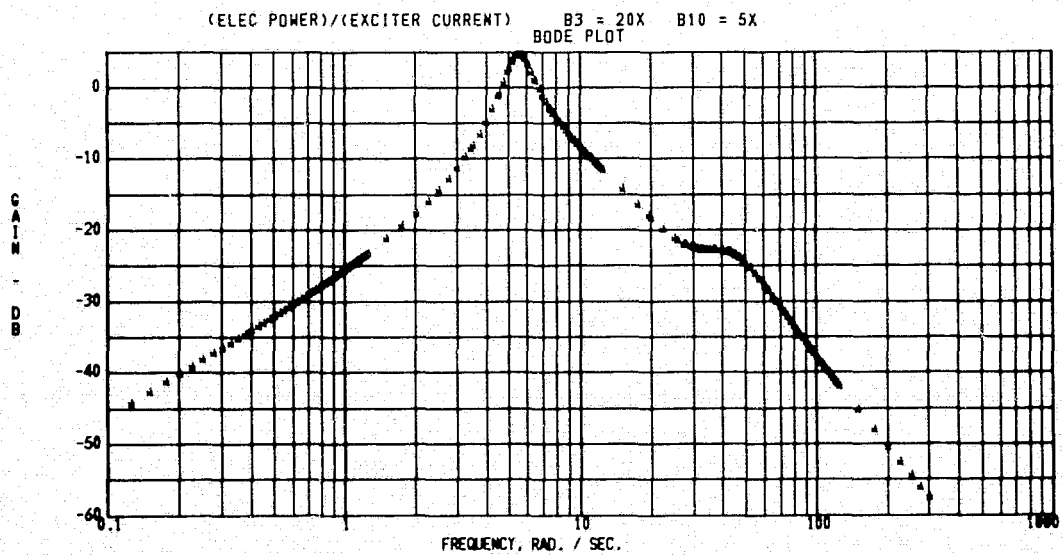


Figure 5. - Electric output power as function of exciter current.

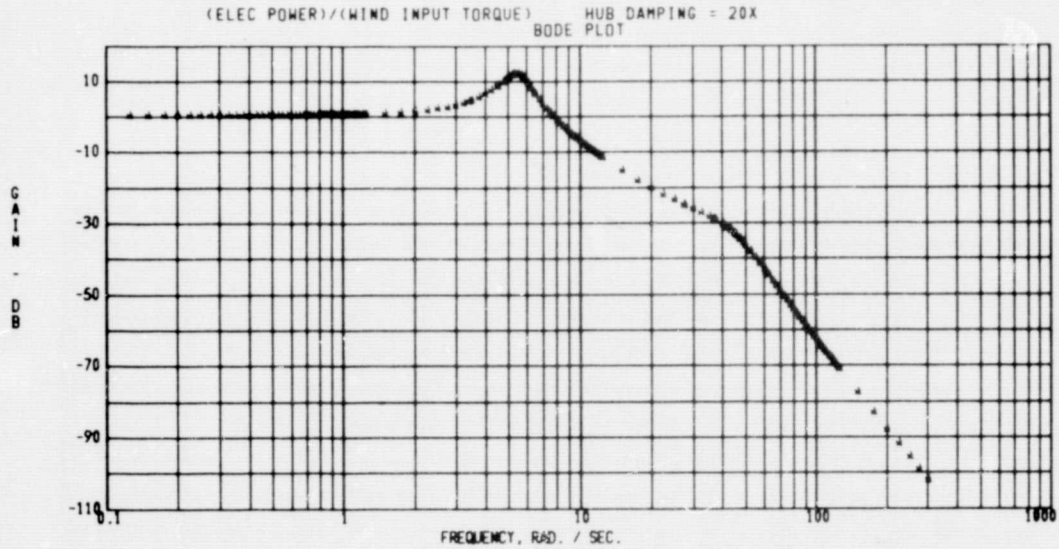


Figure 4. - Frequency response of model in figure 1 but with increased damping.

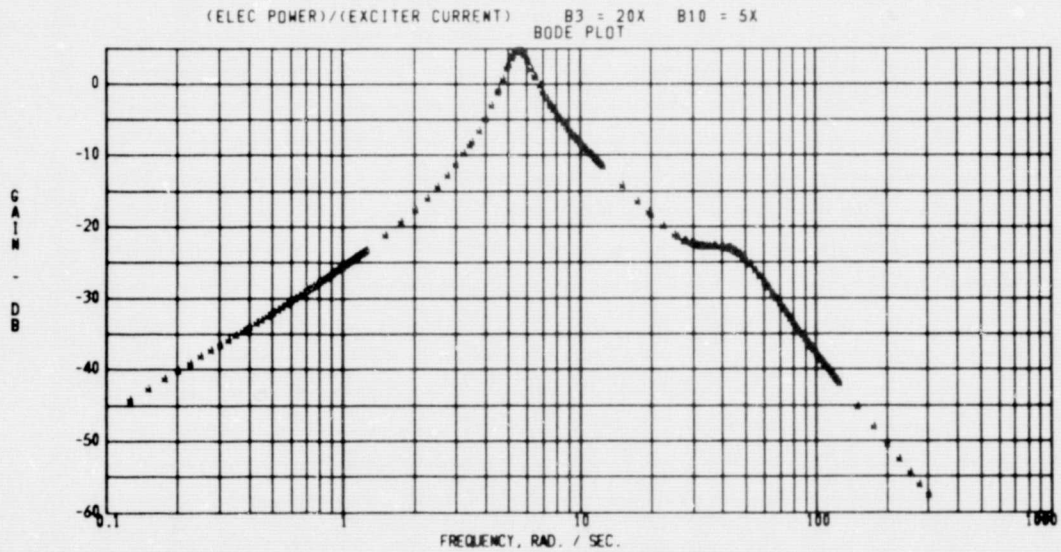


Figure 5. - Electric output power as function of exciter current.

WTG MOD-0, 24FEB77

40 KW, 20 RPM, CONSTANT FIELD CURRENT

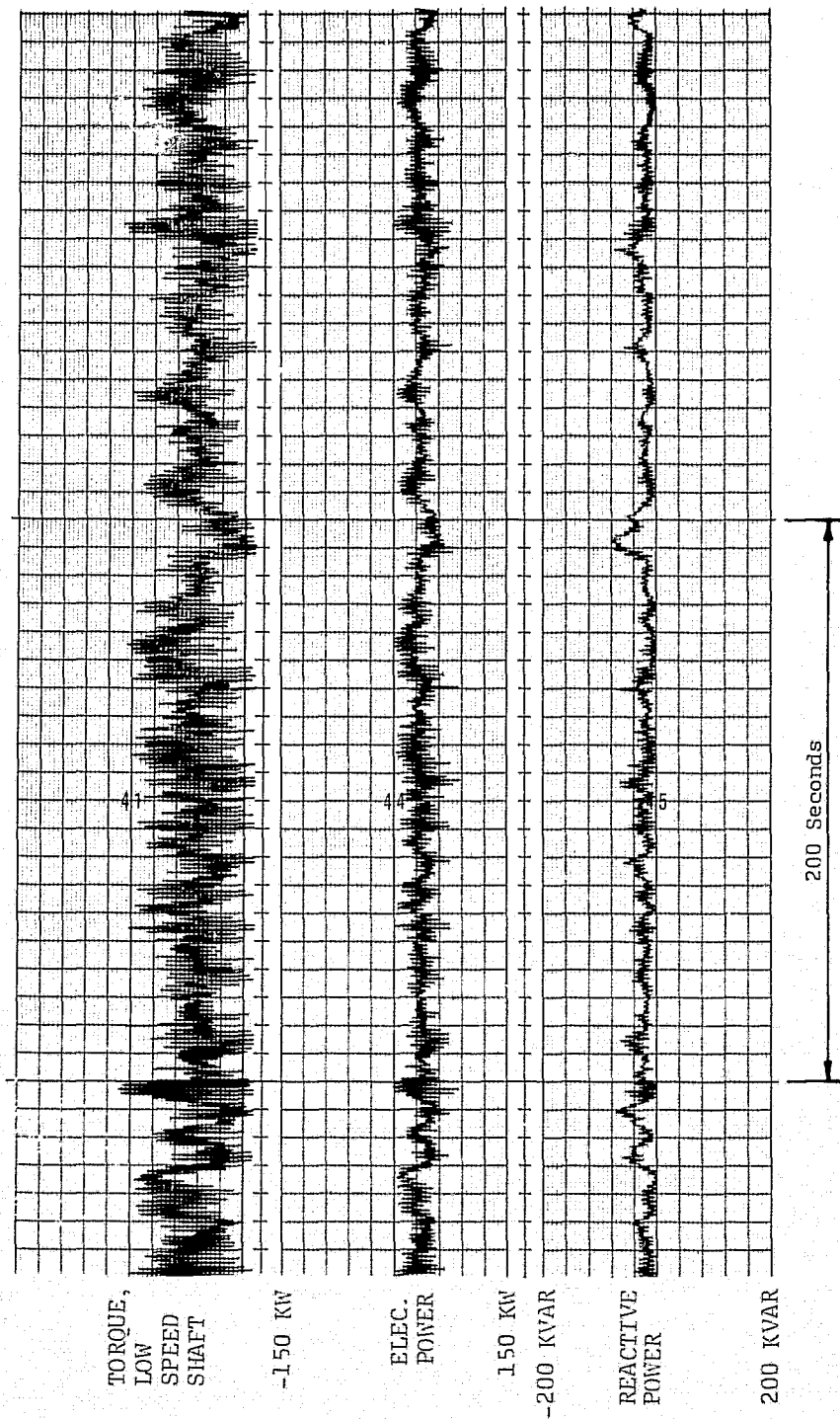


Figure 6. - Test recording of synchronized generator with constant field current.

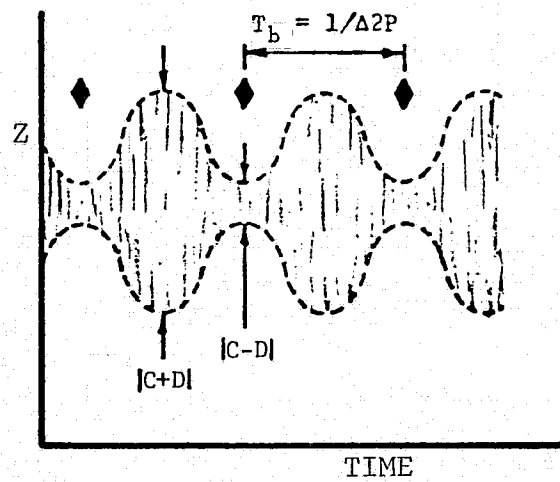
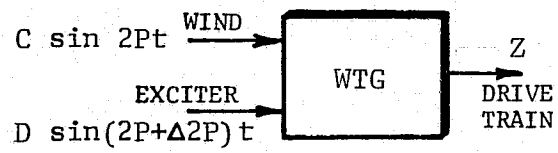


Figure 7. - Diagram of beat frequency test.

WTG MOD-0, 24FEB77

40 KW, 20 RPM, .7 HZ SINUSOIDAL FIELD CURRENT

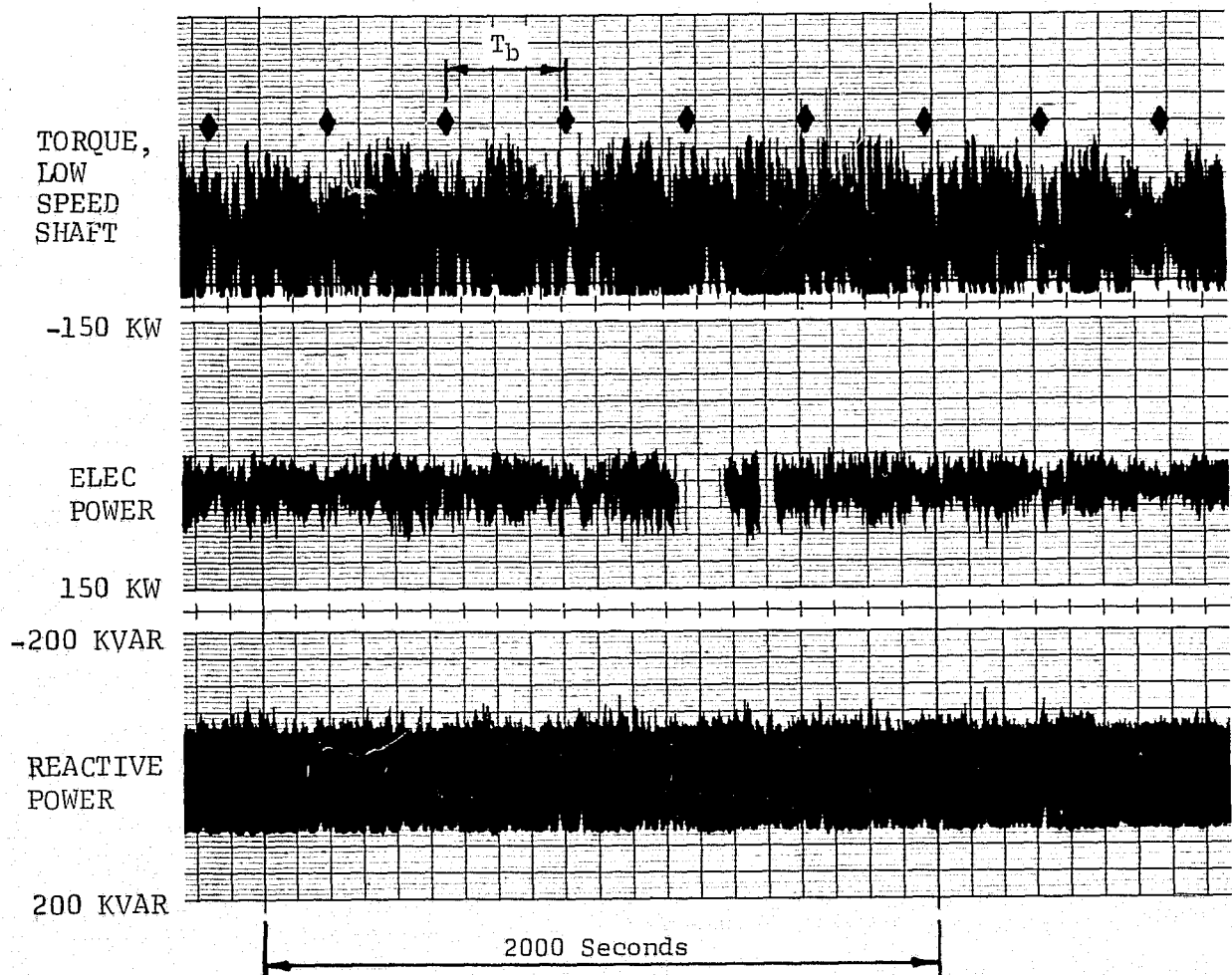


Figure 8. - Test recording of synchronized generator with sinusoidal field current.

WTG MOD-0, 24FEB77

40 KW, 20 RPM, .7 HZ SINUSOIDAL FIELD CURRENT

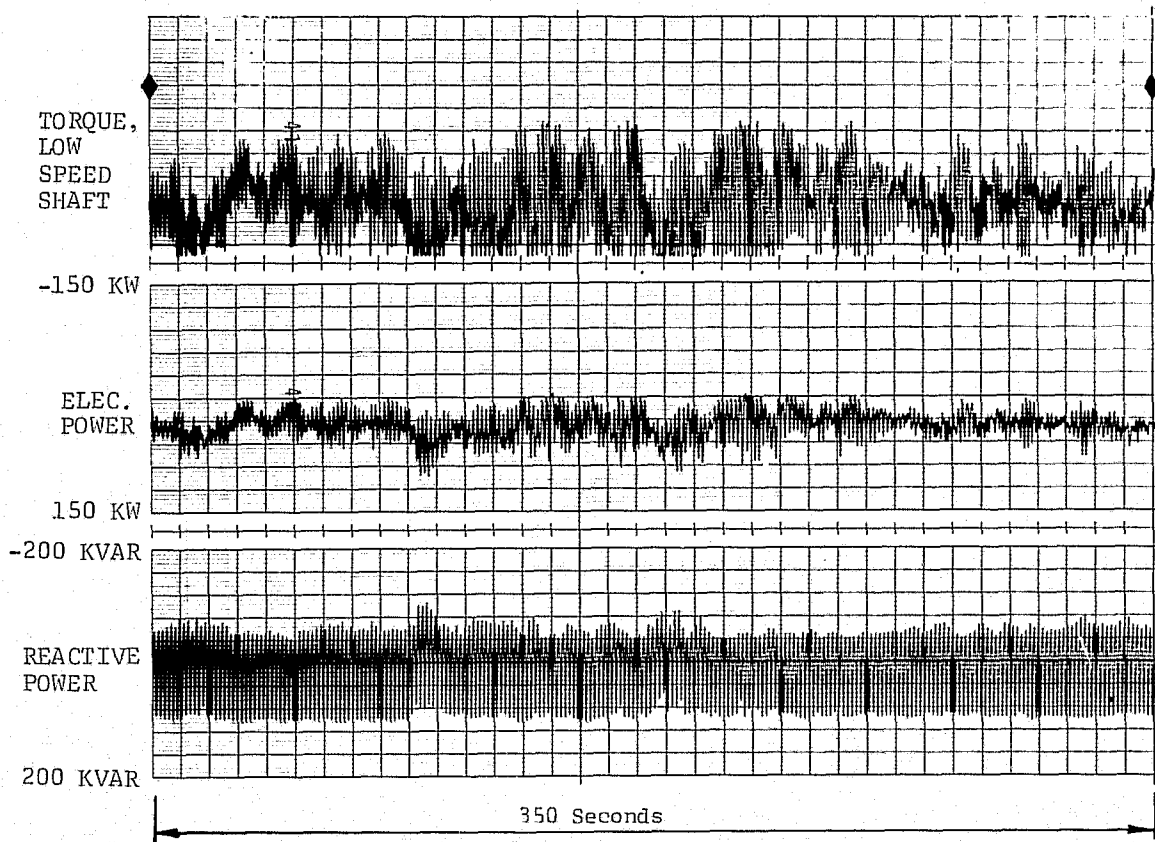


Figure 9. - Test recording of synchronized generator with sinusoidal field current.