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VARIABLE GAIN FOR A WIND TURBINE PITCH CONTROL

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SUMMARY

A variable gain is considered for a wind turbine pitch angle control. The gain variation is made in the software logic of the pitch angle controller. The controller gain is structured to be proportional and integral feedback of power. The gain level is changed depending upon the level of power error. The control uses low gain for low pitch activity the majority of the time. If the power exceeds ten percent offset above rated, the gain is increased to a higher gain to more effectively limit power. A variable gain control functioned well in tests on the Mod-0 wind turbine.

INTRODUCTION

The Federal Large Horizontal Axis Wind Turbine Program explores the utilization of wind energy. The NASA Lewis Research Center under agreements with the U.S. Department of Energy has conducted tests of four Mod-OA wind turbines with 38 meter (125 ft) diameter turbines (ref. 1). The machines have provided data for improving wind turbine designs. One feature of the design that has been maintenance prone is the blade pitch angle mechanism. The pitch angle is the angle at which the turbine blades meet the wind. The blade pitch is varied by an electro-hydraulic servo in a feedback control. The pitch control limits the power by angling the blade to spill excess power. Otherwise, there is the potential for an over-power condition and a possible loss of alternator synchronism with the utility when the wind speed increases rapidly in a wind gust.

The feedback parameter gains in the control determine how fast the pitch responds to power errors. The control gains in current wind turbines are linear constant values (ref. 2). There is a problem with constant gain values. High gain in the controller is required to insure a fast pitch response to avoid over-power. However, high gain tends to create a resonance in the power train. The resonance induced from high gain typically amplifies disturbances between the one per revolution (occuring once per turbine revolution, 1P) and two per revolution (2P) frequencies. The disturbances that are present in this frequency range are generally of low amplitude, but they are present is sufficient quantity to contain considerable energy. Thus, a high gain can produce excessive pitch mechanism activity the majority of the time. On the other hand, a low gain reduces pitch motion and wear but provides less over-power protection in case of wind gusts.

A variable gain, dependent upon the power error, is considered for the software of the pitch controller. A variable gain control can be programmed on a microprocessor with no increase in hardware costs and with only slightly more complexity than a constant gain control. The variable gain provides more freedom by providing high gain for limiting over-power in wind gusts and low gain for reducing general pitch activity. Low gain can be used for the majority of the operating time to control the low amplitude or short duration variations of power below or near rated that do not pose a danger or stability problem to the machine. A switch to high gain is made if the power exceeds an unacceptable percentage above rated.

This report describes analysis and test of a variable gain control for a wind turbine. The responses of constant and dual gain controls are compared, and the potential advantages of a dual gain control are examined. The configuration tested is a variable gain system with a smooth transition between the high and low gain values.

WIND TURBINE DESCRIPTION

An overall view of the type of wind turbine considered for a variable gain pitch control is shown in figure 1. The power train and pitch change components located inside the nacelle atop the tower are shown in figure 2. A hydraulic servo, rotating with the hub, changes the collective pitch. The turbine turns at 40 rpm and the gear box increases the rotational speed to 1800 rpm. There is a fluid coupling between the gear box and the alternator. The alternator is a four pole, 480 volt, synchronous alternator rated for 250 kVA.

POWER TRAIN MODEL

The power train was modelled with lumped springs and masses as represented in figure 3. The alternator model was similar to the structure detailed in reference 2 and was assumed connected to an infinite bus.

A closed loop pitch control schematic is shown in figure 4. The controller gains are proportional and integral feedback of power as structured on Mod-0A machines. The hydraulic pitch actuator dynamics are modeled conservatively as two lags at 9 rad/sec; the actual dynamics may be twice as fast when the hydraulic accumulator is near full pressure. The blade aerodynamic gains, changes in power to changes in wind speed and pitch angle, are assumed to be constants. Constant blade aerodynamic gains are reasonable assumptions in wind speeds at which the pitch control is important (ref. 2).

Arbitrary turbine disturbances are assigned to represent wind effects for the controls analysis. The disturbances are designed to exercise the control and are not deduced from experimental data. A simulated wind gust is a 400 kW disturbance change to the turbine which is smoothed by a double lag at one rad/sec. Another assumed disturbance is a 400 kW peak to peak sinusoid at the 2P frequency. It represents disturbances broadly centered near the 2P frequency that a two-bladed turbine could encounter from spacially nonuniform winds.

RESULTS OF CONTROL ANALYSIS

A Mod-0A power train is analyzed to define its dynamic characteristics and identify control requirements. Analysis in the frequency domain is used to examine resonances in the power train created by constant gain pitch controls. Analysis in the time domain is used to examine a nonlinear dual gain controller.

Power Train Dynamics With No Pitch Control

Calculated responses of a Mod-OA power train are shown in figure 5. The responses show the power train frequency response dynamics with no pitch control. The plots of alternator power to disturbances in turbine rotor power are normalized to a steady state value of one. There is a resonance that peaks near the 1P frequency of 0.67 Hz., for a low fluid coupling slip of 0.1 percent (per 200 kW). The resonance occurs because the turbine blades oscillate on the springs of the low speed shaft and (electrical "spring") of the alternator. The resonance is a potential problem because it amplifies in a frequency range with abundant disturbances. Disturbances near the 2P frequency of 1.33 Hz. are attenuated to 0.36. A relatively small slip in the fluid coupling of 1 percent damps the resonance and attenuates the response at the 2P frequency to 0.26. With a fluid coupling slip of 3 percent, the response at the 2P frequency is attenuated to 0.16. The baseline for further control studies reported here is a 3 percent slip. This baseline power train was identified for later time response studies to be dynamically equivalent to lags at 1.5 and 14 rad/sec.

Integral Gain Pitch Control

The system dynamics with integral gain in the pitch control are shown in figure 6. Integral control sums error with respect to time and is seen effective in reducing the error below the "no control" case up to frequencies of 0.14 hertz. For example, with a 0.04 (deg/(sec*kW)) integral gain, the response is 0.04 at 0.01 hertz. This means a 400 kW zero to peak rotor power (16 mph zero to peak gust in wind speed) slow sinusoidal disturbance causes a generator over-power change of only 16 kW. The same control is seen to induce a resonance that crosses above the "no control" case near 0.14 Hz. The resonance limits the value of pure integral gain to less than 0.04.

Proportional Control

System responses with proportional, but no integral, control are shown in figure 7. With a high proportional gain of 0.1 (deg/kW), the steady-state attenuation is 0.2 and the system response is below the "no control" case out to nearly 0.5 hertz. A resonance created by the 0.1 gain proportional control amplifies disturbances near the 2P frequency about 1.5 times the "no control" case. The resonance limits the value of pure proportional gain to less than 0.1.

Proportional Plus Integral Control

System responses with both proportional and integral control gains, the structure normally used, are shown in figures 8(a), (b), and (c) for high, medium, and low integral gain settings respectively. The system with a high 0.1 integral gain, unstable by itself, is stable when combined with proportional gain. The figure 8(a) case of high 0.1 integral and 0.1 proportional gains provides attenuation out to 0.5 hertz in a manner characteristically desired to prevent over-power in wind gusts. The proportional gain removes the resonance created by high pure integral gain. But the remaining resonance near the 1P frequency is caused primarily by the high proportional gain. A dual gain control discussed in the following section allows operation with the resonance and higher gains. Lower gains for general operation could be an integral gain between 0.02 to 0.04 and a proportional gain between 0.01 and 0.02 as shown in figures 8(b) and (c).

It is noted that a high gain control with a 2P notch filter is not a simple solution for the Mod-0A machines. A notch broad enough to span the 2P disturbance tends to increase the original resonance created by the control near the 1P frequency.

Dual Gain Controls

A dual gain control that switches gain depending on the power error is a concept proposed to operate with high gain only when the power exceeds an offset above rated. Because a control with a variable gain makes the analysis nonlinear, the system is analyzed with time responses computed on an analog computer where the gain is switched between two discrete values at 10 percent above rated power. Otherwise, the system has the same linear plant used for the frequency analysis, with the exception that the power train is the simplified two lag dynamics discussed earlier. Values for the dual gain are 0.02 integral and 0.01 proportional (refer to fig. 8(c)) for power below a 10 percent, 20 kW, offset and 0.1 integral and 0.1 proportional (refer to fig. 8(a)) for power error above the offset.

Responses to the gust-like disturbances with a dual gain control are shown in figure 9(a). The dual gain control is seen more effective than a constant low gain in limiting over-power. The high gain of the dual gain limited the over-power peak to only 40 kW above set point in an up-gust disturbance, (from a relative -200 kW to +200 kW disturbance). For comparison, in a decreasing change the power dipped 140 kW, (from a relative +200 kW to -200 kW disturbance). The smaller 40 kW, rather than 140 kW, error is the benefit of the higher gain in the dual gain control for over-power errors.

The potential problem of excessive pitch motion in normal operation is illustrated with a disturbance at the 2P frequency in figure 9(b). The relative responses are compared for the dual, high, and low gain controls. The pitch activity with the dual gain control is almost as low as with the constant low gain control. By comparison, however, the constant high gain increases the 2P output power oscillation by a third and the pitch response over ten times. The benefit of the dual gain is markedly lower pitch activity than with the constant high gain.

RESULTS OF Mod-0 TESTS

A variable gain control was briefly tested on the Mod-0, a research wind turbine. The Mod-0, a precursor of the Mod-0A machinces, is the same size but rated for 100 kW rather than 200 kW (ref. 3). In the tests made, the winds ranged from about 20 to 25 mph and the power set point was 50 kW. The variable gain appeared to function well.

The spectrum of the pitch responses measured in operations with constant and variable gain controls are shown in figure 10. The variable gain function, also shown in figure 10, was obtained by including in the control loop a multiplier that varied between 0.33 and 3.3 when the power exceeded a 10 kW offset. The variable proportional gain then varied between 0.03 and 0.3 and the variable integral gain, between 0.014 and 0.14. The spectral data shows that despite a proportional gain as high as 0.3, the general 2P activity was lower with the variable gain control than with the constant (0.094 proportional and 0.044 integral) gains. The measured rms pitch position activity at the 2P frequency was about one-half (7 db less) with variable gain, a comparison that might vary depending on the wind speed conditions.

CONCLUDING REMARKS

A concept was investigated in which the feedback gains of a wind turbine pitch angle controller were varied depending upon the power error. The gains were low for the normal range of power errors and high if the power error exceeded a ten percent offset above set point. The variable gain study included both analysis and test. The analysis predicted the variable gain could lower pitch activity significantly during normal operations and also improve the limiting of over-power in wind gusts. In tests, the variable gain concept appeared to function well. The general pitch activity was reduced. A variable gain pitch control merits consideration in future wind turbine designs.

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2. Seidel, Robert C.; Gold, Harold; and Wenzel, Leon M.: Powerr Train Analysis for the DOE/NASA 100-kW Wind Turbine Generator, NASA TM-78997, 1978.

3. Glasgow, J.C.; and Birchenough, A.G.: Design and Operating Experience on the U.S. Department of Energy Experimental Mod-0 100-kW Wind Turbine. DOE/NASA/1028-78/18, NASA TM-78915, 1978.

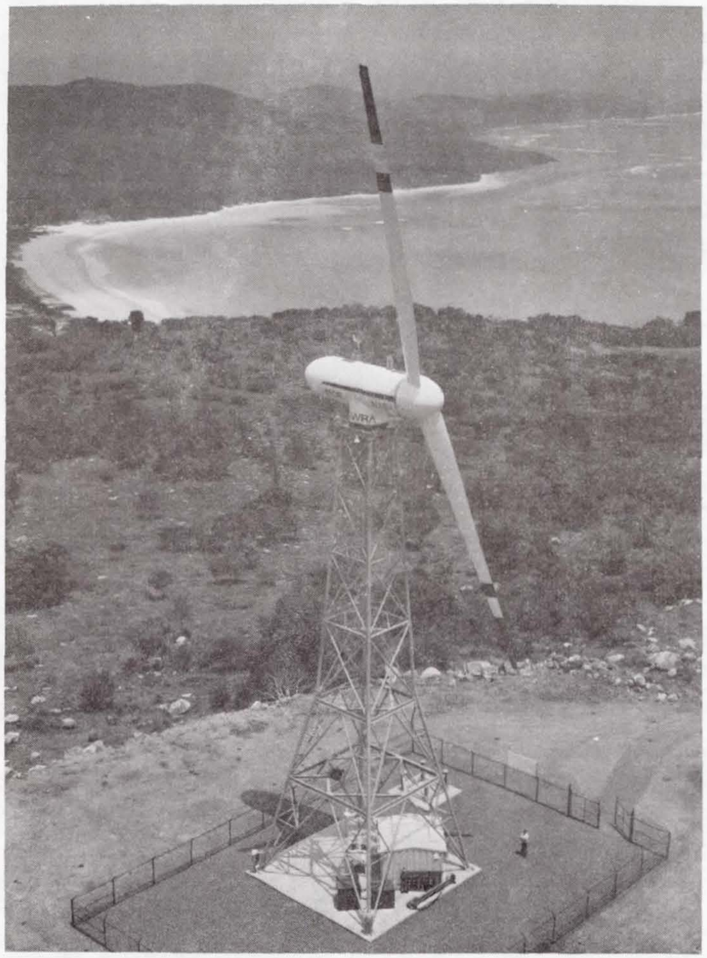


Figure 1. - Mod-OA DOE/NASA 200-kW experimental wind turbine in Culebra Island, Puerto Rico.

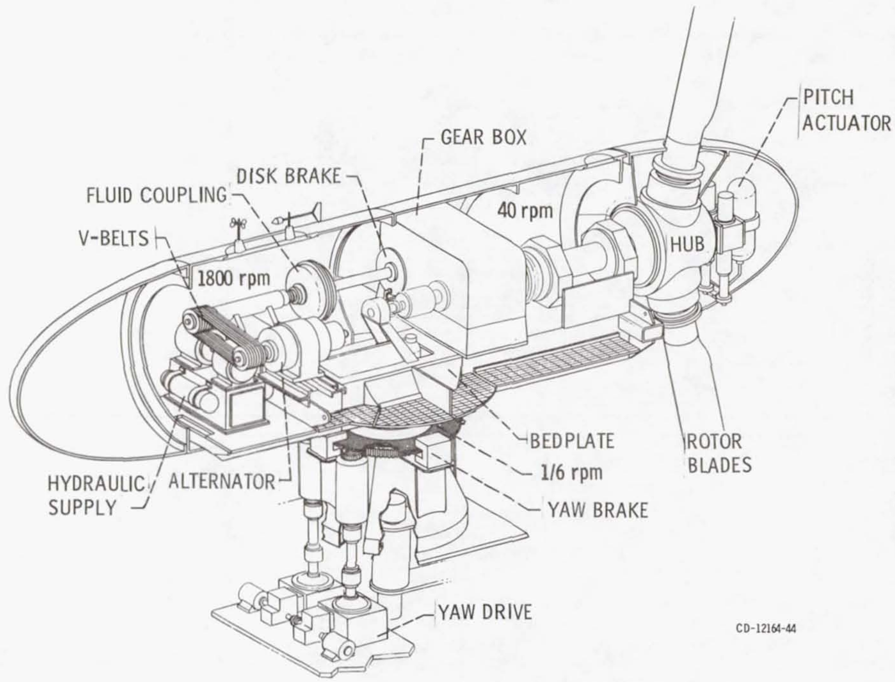


Figure 2. - Wind turbine generator, schematic of nacelle interior.

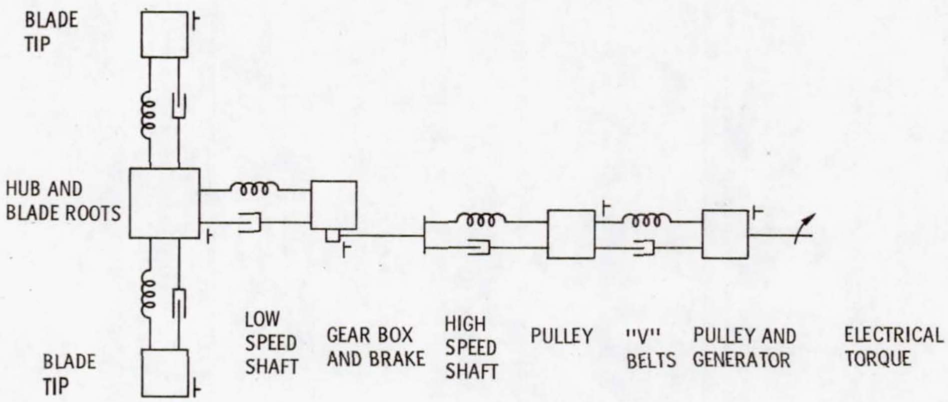


Figure 3. - Block diagram of power train model showing inertial masses, torsional springs, and dampers.

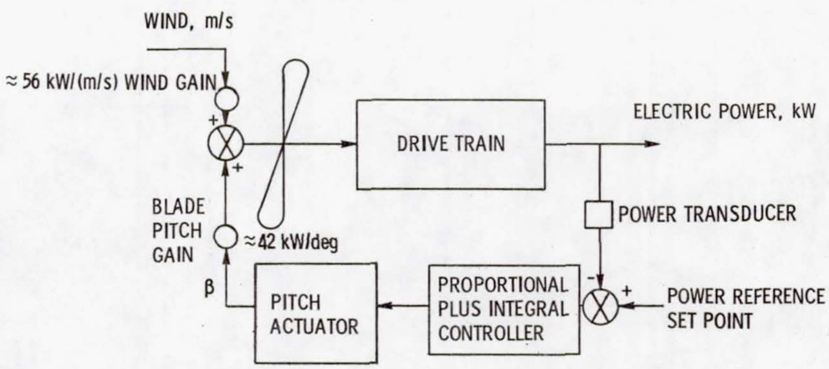


Figure 4. - Block diagram of closed loop power control.

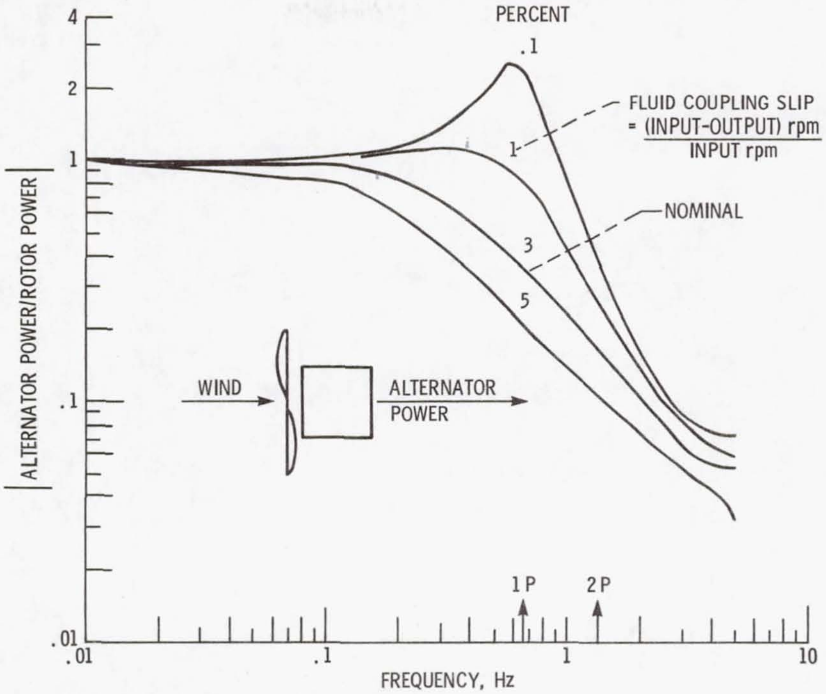


Figure 5. - Calculated frequency response for a Mod-OA power train for slip rates of 0.1 to 5 percent per 200 kW.

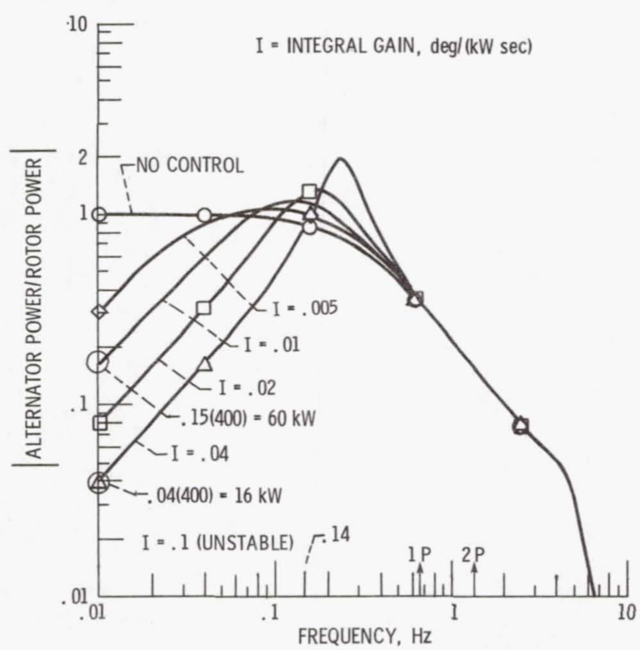


Figure 6. - Calculated responses of the power train with pure integral gain in the pitch control.

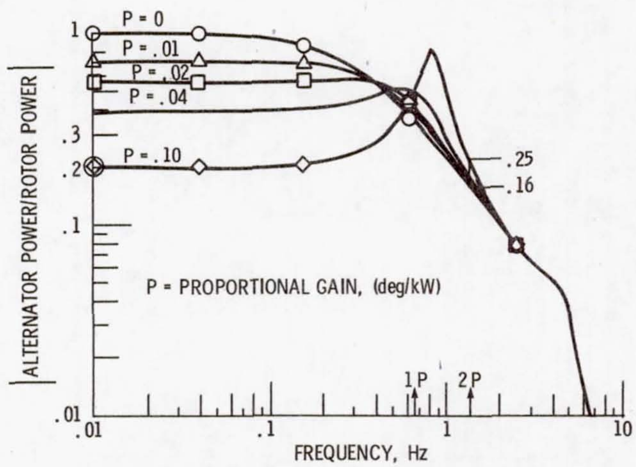
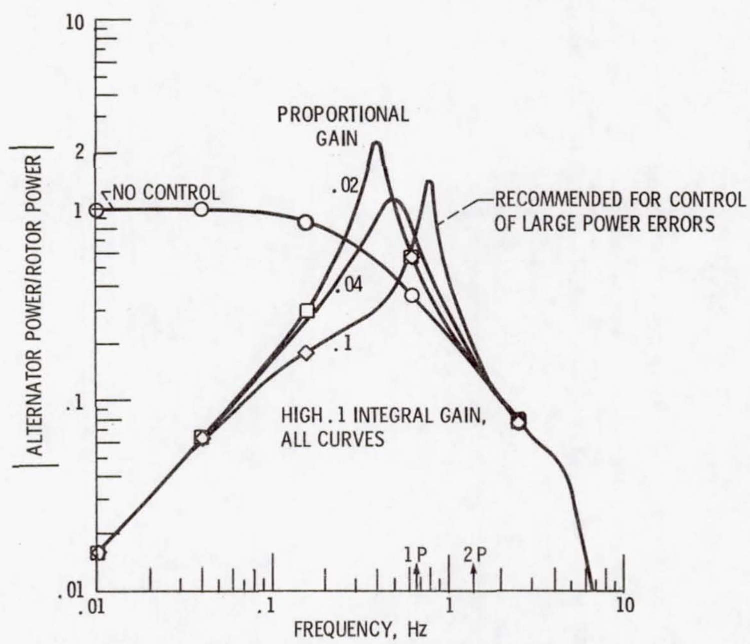
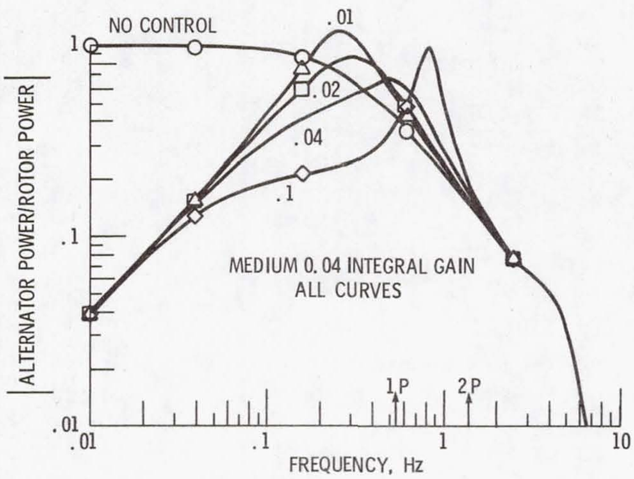


Figure 7. - Calculated power train responses with pure proportional gain control.



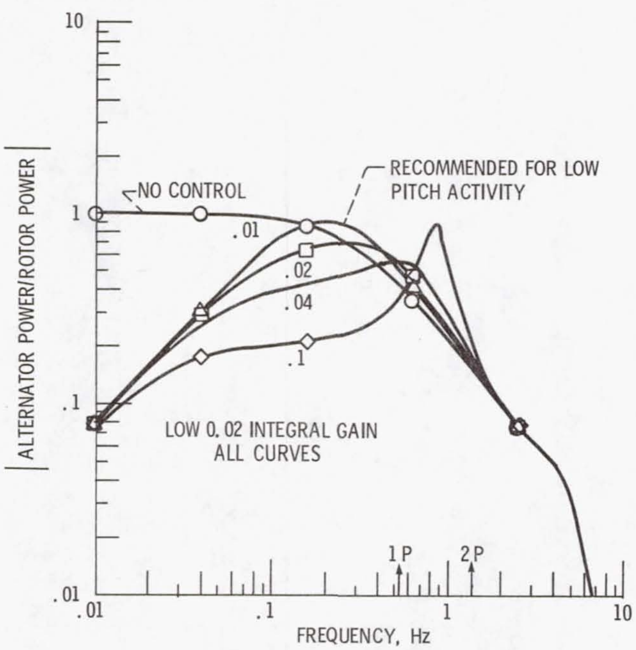
(a) HIGH 0.1 INTEGRAL GAIN; (0.02, 0.04 and 0.1) PROPORTIONAL GAIN CURVES NOTED.

Figure 8. - Power train responses with proportional plus integral control.



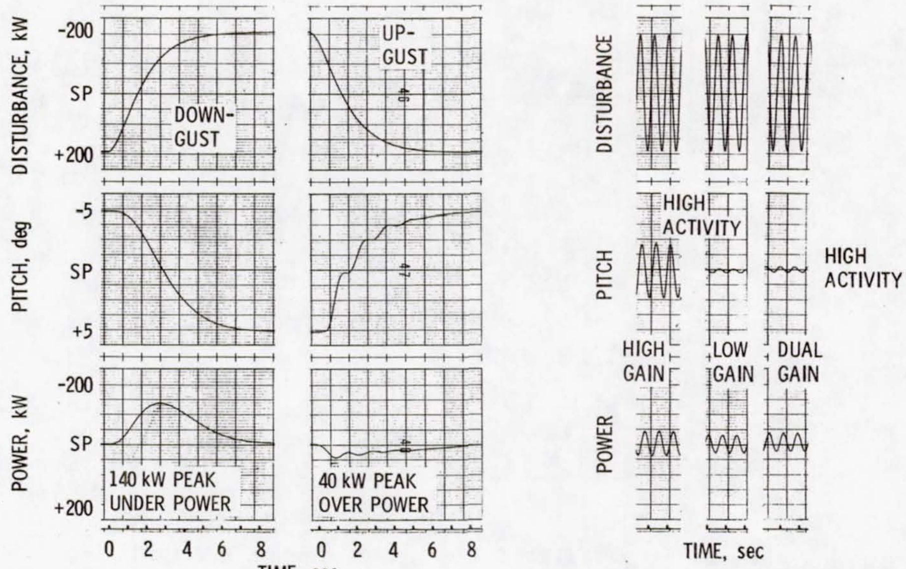
(b) MEDIUM 0.04 INTEGRAL GAIN; (0.01, 0.02, 0.04, and 0.1) PROPORTIONAL GAIN CURVES NOTED.

Figure 8. - Continued.



(c) LOW 0.02 INTEGRAL GAIN; (0.01, 0.02, 0.04, AND 0.01) PROPORTIONAL GAIN CURVES NOTED.

Figure 8. - Concluded.



(a) SIMULATED WIND GUSTS - DUAL GAIN CONTROL

(b) SINUSOIDAL DISTURBANCE AT 2 PER REV. FREQUENCY.

Figure 9. - Analog computer perturbation responses around set point (SP).

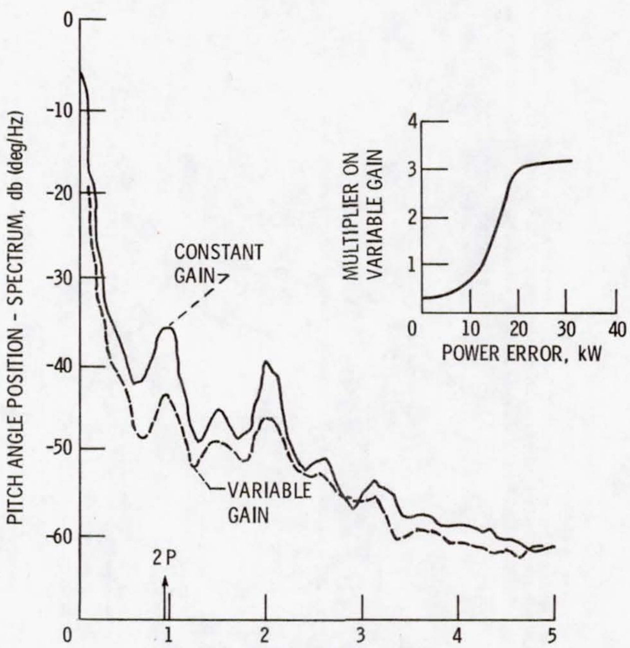


Figure 10. - Overlay of pitch activity spectra from two consecutive 5.4-min runs. Mod-0 turbine speed 30 rpm. Constant gain 0.094 proportional and 0.045 integral. Variable gain, 0.3 to 3.3 multiplier to constant gains, as shown.

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16. Abstract

A variable gain is considered for a wind turbine blade pitch angle control. The gain is changed depending upon the level of power error. The gain is low for low pitch activity the majority of the time. The gain is increased to more effectively limit power if the power exceeds a ten percent offset above rated.

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