

USE OF BLADE PITCH CONTROL TO PROVIDE POWER TRAIN  
DAMPING FOR THE MOD-2, 2.5-MW WIND TURBINE\*

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ABSTRACT

The Control System for the MOD-2 wind turbine system is required to provide not only for startup, RPM regulation, maximizing or regulating power, and stopping the rotor, but also for load limiting, especially in the power train. Early operations with above-rated winds revealed an instability which was caused primarily by coupling between the quill shaft and the rotor air loads. This instability caused the first of several major Mod-2 Control System changes which are reviewed in the paper.

Experience with Mod-2 operations, starting in early 1981, convincingly showed that power train damping was a mandatory addition to the array of control system functions.

At that point in the Mod-2 development, the control system had the configuration illustrated in Figure 2, power train damping having been provided through hub rate error feedback. Several other features of this control system are noteworthy:

INTRODUCTION

The need for power train damping on the Mod-2 Wind Turbine system (WTS) arose from a series of design choices, the principal ones being

- o Selection of steel for the 300 ft diameter rotor, resulting in a large polar moment of inertia,
- o Use of a two-element rotor shaft arrangement: a hollow, low-speed shaft for reacting rotor mass and normal loads and moments, and a central quill shaft for transmitting rotor torque to the remainder of the power train,
- o Selection of a relatively low torsional stiffness for the quill shaft to reduce response to two-per-revolution torques and favor longer fatigue life.

- o Blade schedule switching at below-rated conditions to improve energy capture,
- o Control mode switching between below-and above-rated conditions,
- o Proportional control for short-term power regulation and integral control for long-term regulation,
- o Notch filter to reduce blade activity at the two-per-revolution (2P) frequency (0.58Hz)

The quill shaft is coupled to a synchronous generator through a step-up gear box and high speed shaft (Figure 1). In a power-generating mode, the synchronous generator rotor is locked to the interfacing power grid frequency tightly enough that the power train behaves (dynamically) very nearly as if the generator were fixed to ground. The resulting natural frequency is 0.14Hz and its motions are lightly damped.

Below-rated-power operations employed a blade pitch schedule designed for near-maximum energy capture but maintaining positive control authority; namely, an increase in blade pitch should produce a reduction in power. This schedule is shown on Figure 3 which also notes the blade pitch mechanical limit at -5 deg. As indicated on the figure, "hysteresis" was also provided to reduce schedule- and mode-switching activity. At above-rated conditions control was effected through the proportional, integral and hub rate error loops to regulate power at 2.5 MW.

INITIAL CONTROL SYSTEM

The initial system for controlling blade pitch was designed to accomplish a number of functions:

- o Startup, in which rotor aerodynamic torque is employed to accelerate the power train to synchronous speed,
- o RPM regulation prior to generator synchronization
- o Maximizing power in below-rated-power winds
- o Regulating power in above-rated-power winds
- o Limiting rotor loads in the presence of gusts, and
- o Shutdown (in non-emergency situations), in which the rotor is decelerated to a stop.

In use, this control system generally produced tight power regulation with above-rated winds but had relatively high blade activity at the tower natural frequency (0.37Hz). Its least attractive quality, however, was that it occasionally allowed large amplitude, unstable oscillations near the power train natural frequency to develop at near- and above-rated power conditions. As Figure 4 shows, these events developed very rapidly and were only terminated by entering the shutdown mode, usually involuntarily. Test data indicated that blade pitch excursions to low angles - often to the mechanical stops - were occurring. It seemed evident that the resulting control authority reversals both initiated and sustained such oscillations. The specific cause for the initial blade pitch excursions was not pinpointed but noise in the hub rate error signal was suspected. Blade pitch limits which prevented loss or reversal of control authority were then implemented in the software and effectively eliminated unstable coupling between the power train and control system. A notch filter to reduce blade activity at the tower frequency was also added.

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At this stage of its development, the initial control system had evolved into one which had materially improved availability of the Mod-2 but still had four significant problems to be solved:

- 1) Noise on the hub rate error signal,
- 2) Transients caused by mode switching,
- 3) Operation away from maximum power blade angles with below-rated winds, and,
- 4) Low stability margins, principally because of the tower and 2P notch filters.

The need to solve these problems set the stage for a new approach to the control system design.

#### NEW CONTROL SYSTEM

Basic requirements dictated that certain features - proportional and integral control loops and the blade pitch subsystem loop - be retained. Solutions for the four problems noted were developed as outlined below:

##### Hub Rate Error

The hub rate signal is obtained from an encoder on a rim of the low speed shaft. The signal is noisy because of encoder sampling and because it responds to both shaft vibration and variations in rim concentricity. Nominal hub rate is subtracted from the noisy hub rate to obtain hub rate error, a process which results in a low signal to noise ratio and causes spurious blade activity. It was observed that hub rate and power rate were highly correlated. Therefore, a differentiating circuit was incorporated in the new design and the derived power rate filtered and summed with the proportional and integral signals as shown in Figure 5. By removing the hub rate error measurement noise, the use of power rate allows higher rate gains and increases system damping.

##### Mode Switching

With the initial control system, even as modified, variations in wind speed about the rated power point caused switching transients between the below- and above-rated control modes. This problem was eliminated by employing the power control mode both above and below rated power. The below-rated blade pitch schedule was made to follow the blade limit so that blade pitch is commanded to the limit. This approach also reduces below-rated blade activity substantially. The limit has been shaped to more closely follow the maximum power curve below 1 MW as indicated on Figure 6.

##### Operation Away From Maximum Power Blade Angles

The new blade pitch control law commanding the blade to the limit when below rated power improves energy capture to the maximum extent consistent with maintaining positive control authority. Additional stability margin has been provided for WTS #5 so the blade pitch limit is set at slightly higher angles, indicated on Figure 7, than for WTS #1 to #4 (Figure 6).

#### Destabilization Due to Notch Filters

Analytical studies were performed to improve stability margins at the power train frequency. The changes permitted slightly greater blade activity at tower frequency but increased phase margin and provided better damping of the power train. The 2P notch filter was revised to allow higher rate gains without amplifying 2P response.

Proportional, integral and derivative gains and rate filter time constants were adjusted to increase system stability and still provide satisfactory attenuation of tower bending excitation.

#### TEST RESULTS

Initial testing of the new control system was done with WTS #2 at Goldendale, Washington, beginning in early September, 1982. The results gave every indication that the goals of the new design had been achieved, namely,

- o The system was well damped - Figures 8 and 9
- o Energy capture generally matched predictions - Figure 10
- o Above-rated power was regulated within  $\pm 200$  KW - Figure 9

In addition, below-rated blade activity was lowered by more than 50 per cent and 2P oscillation amplitudes reduced.

Installation of the new control system in WTS #5 was done in late October, 1982, and results were similar to those observed on WTS #2. After almost two uneventful months of operation, WTS #5 entered a divergent oscillation which resulted in a generator overcurrent shutdown in winds described by site personnel as extremely gusty and over 40 mph. Examination of the data, included in Figure 11, indicated that the instability occurred at a frequency of 0.26 Hz and was primarily a control system mode.

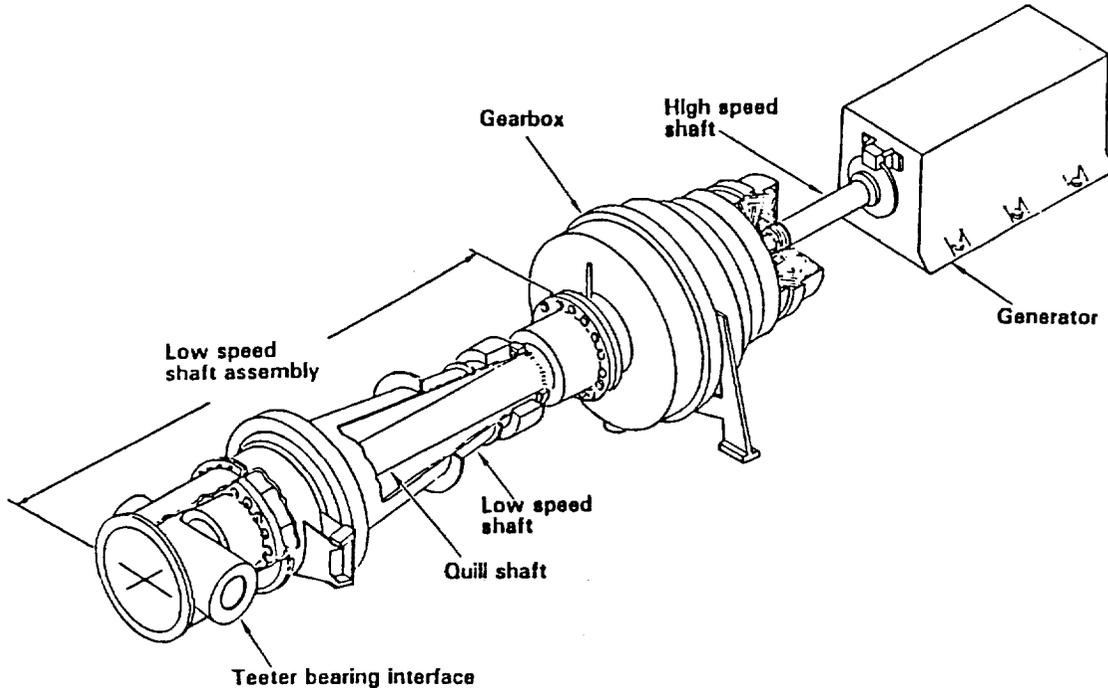
Additional detailing of the simulation mathematical model and analyses pinpointed the increase in blade control authority with increasing wind speed as the culprit. Accordingly, provisions were incorporated to reduce the above-rated proportional and derivative gains in a manner which gradually reduces the overall system gains as wind speed increases. An additional conservatism was included by halving the proportional loop gain (Figure 12). Initially tested in March, 1983, this version of the new control system is installed in all five Mod-2's and has demonstrated that the stability problems have been solved but gust response and power regulation have suffered. At this writing, the development activity is aimed at improving the balance between stability and power regulation.

## CONCLUDING REMARKS

Development of the control system for the Mod-2 wind turbine system has been a learning experience. In the beginning, this system was conceived as being an uncomplicated means for controlling a relatively simple device. This conception dovetailed neatly with the universal need to keep new project development costs low and the initial control system design was accomplished at a modest cost. Once Mod-2 operations began, the need for additional development effort became evident and, over the succeeding two-plus years, the control system grew to be nearly as complex as a contemporary launch vehicle or missile. The development cost, much of it funded by Boeing, has been much greater than originally projected.

In retrospect, it seems evident that additional effort put into developing a more detailed, comprehensive simulation could have helped avoid some of the problems which were encountered. However, operating experience was also needed to identify the really significant details and, especially, to determine the ways in which the real wind turbine and its environment differed from the analytical models.

For the present and future, the lesson learned from the Mod-2 control system development is this: the system analysis and design work must be supported with sophisticated simulation capabilities and be performed by a staff of skilled, experienced control system engineers. This is the approach we have applied to the Mod-5B.



**Figure 1 - Power Train**

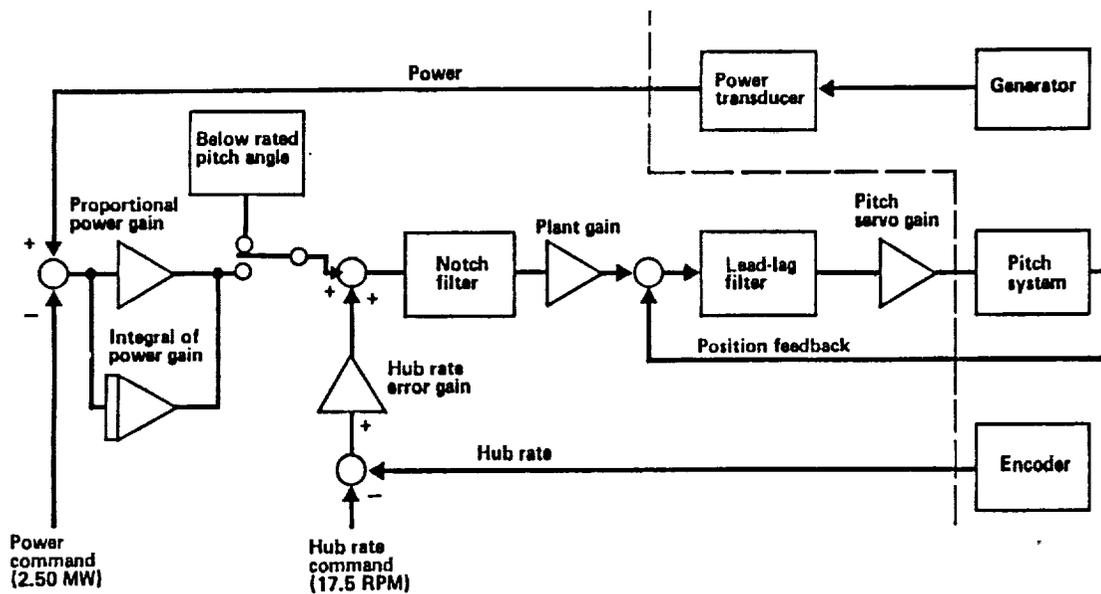


Figure 2 - Initial Control System Functional Diagram

Standard Sea Level Conditions  
April 1982 Configuration

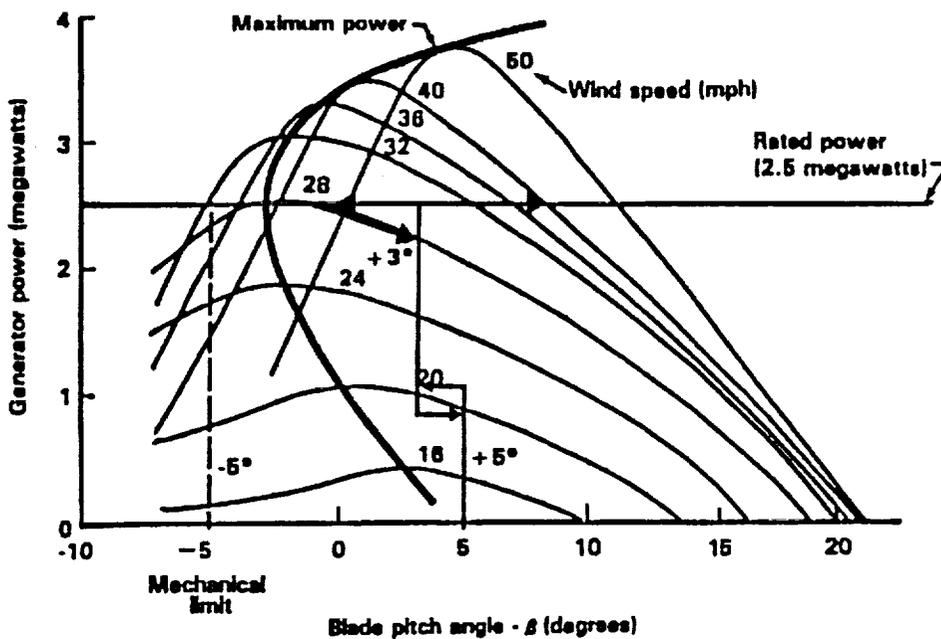


Figure 3 - Original Pitch Schedule

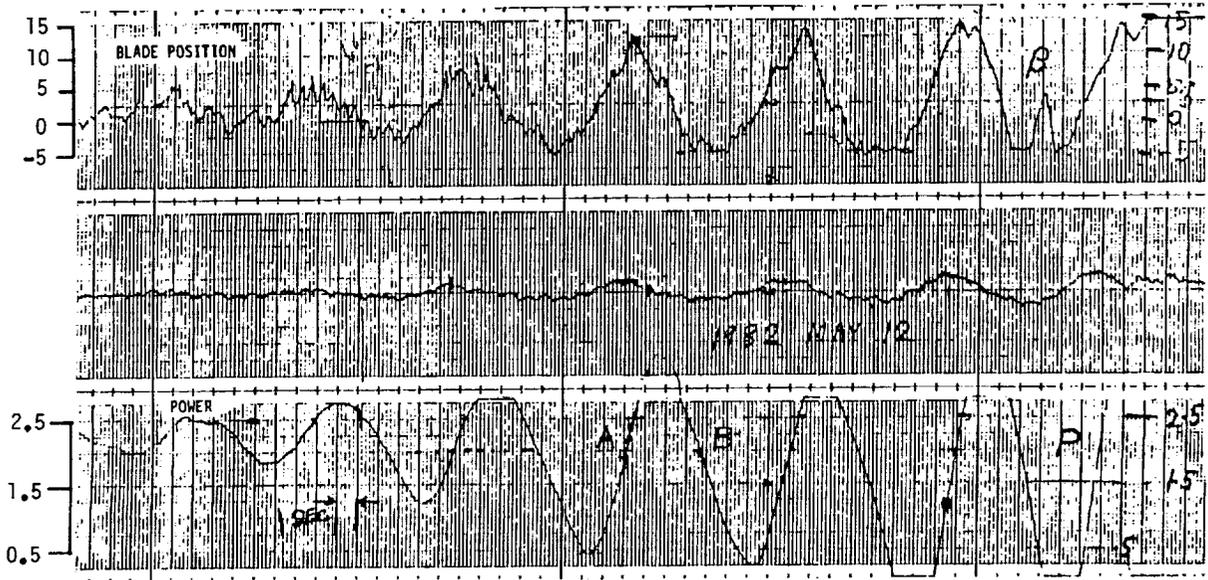


Figure 4 - WTS#2 Power Oscillation, May 12, 1982

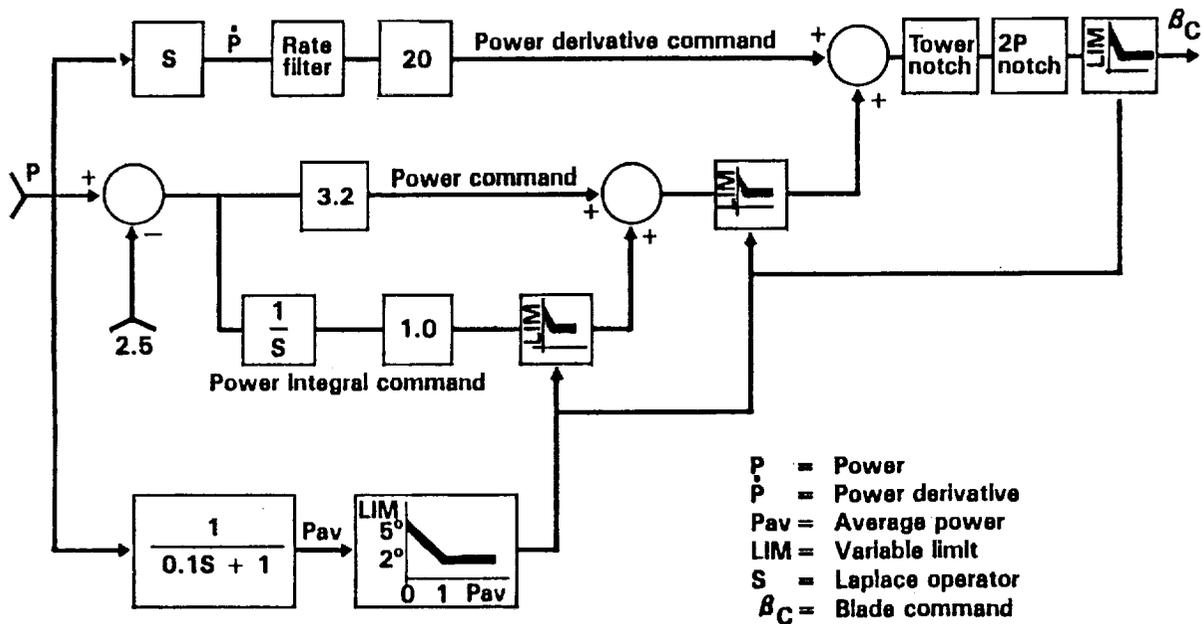
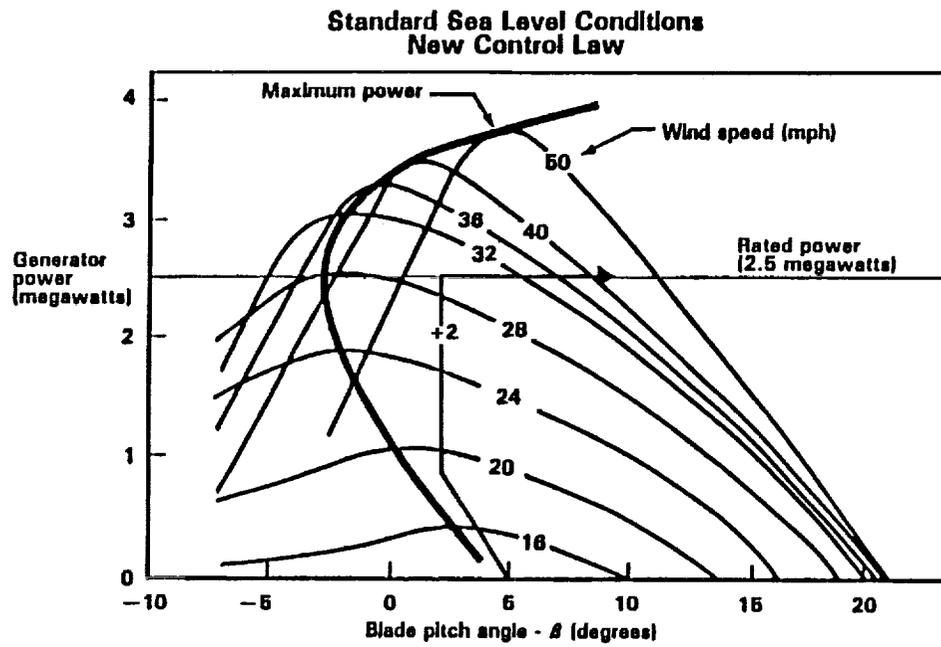
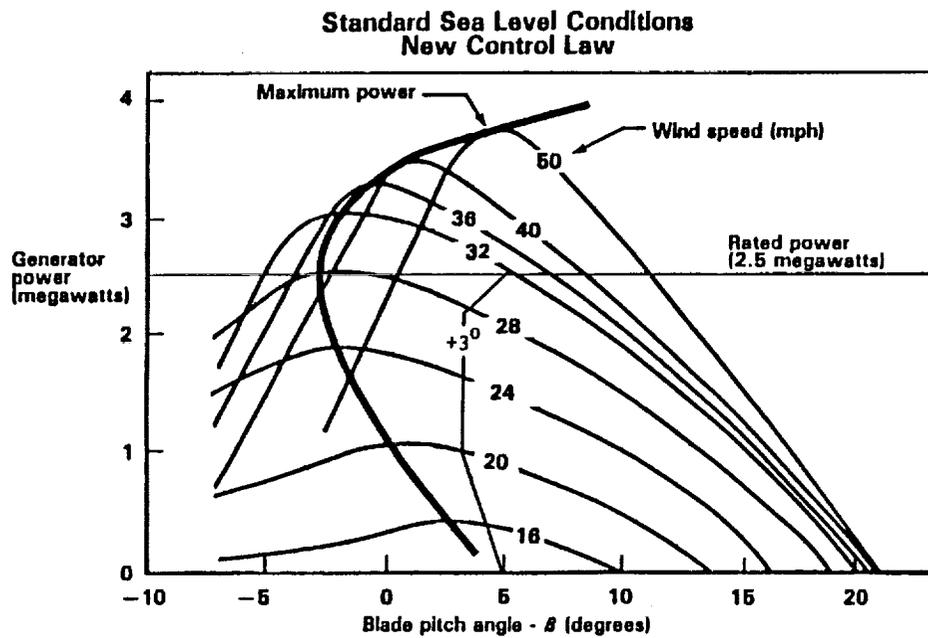


Figure 5 - New Control System Functional Diagram



**Figure 6 - New Pitch Schedule, WTS#1 - #4**



**Figure 7 - New Pitch Schedule, WTS#5**

DATE 10-26-82 TIME 10:54AM

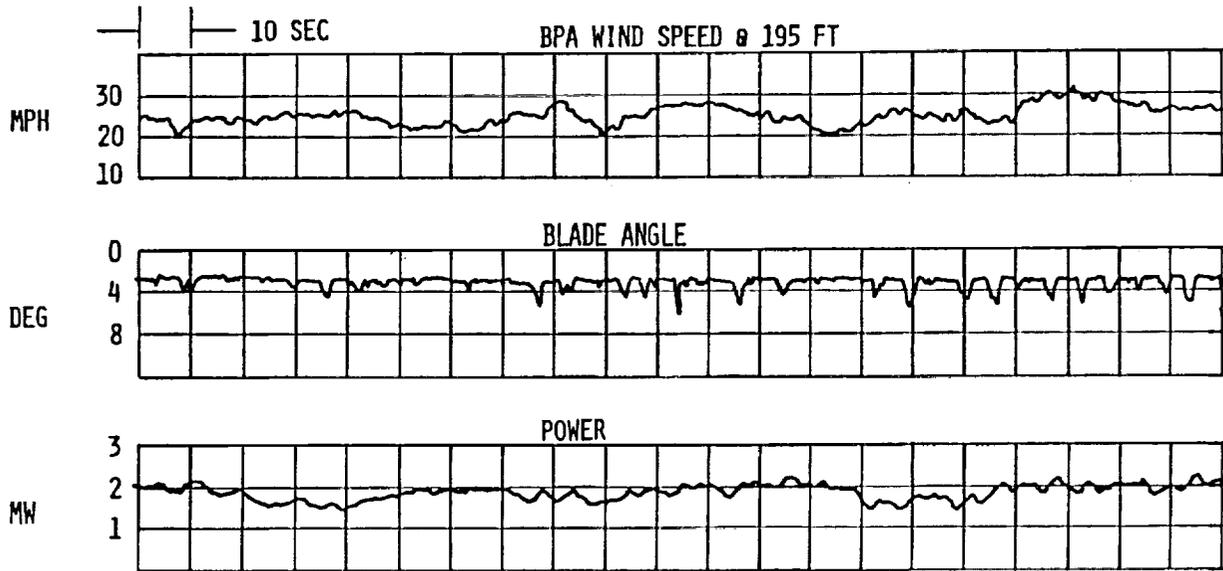


Figure 8 - WTS#2 Performance - Below Rated Power

DATE 10-26-82 TIME 3:30PM

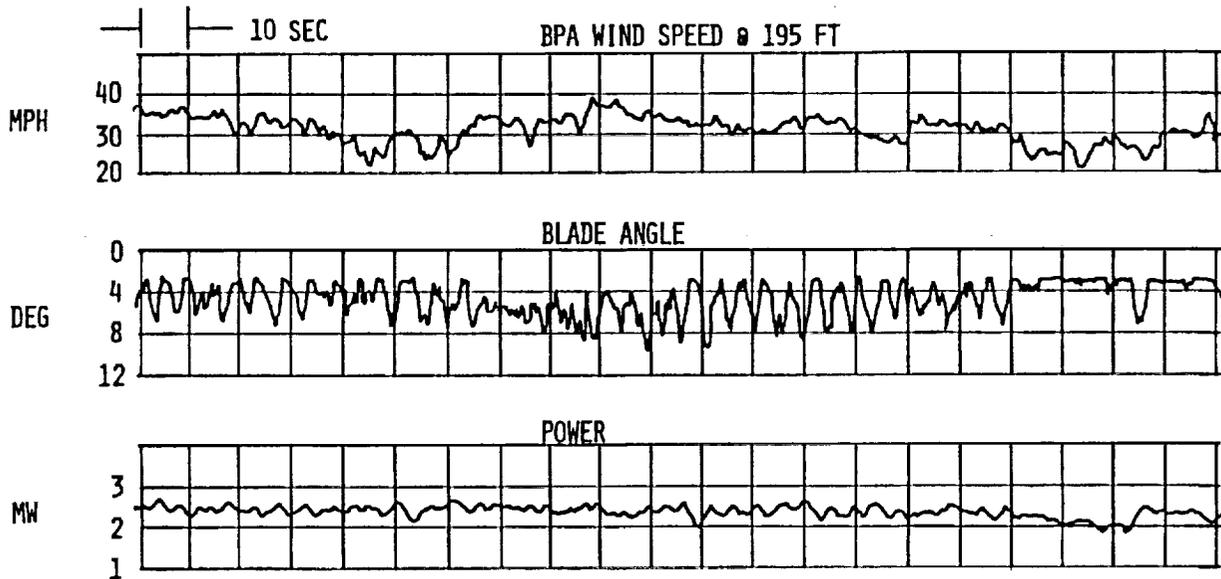


Figure 9 - WTS#2 Performance - Above Rated Power

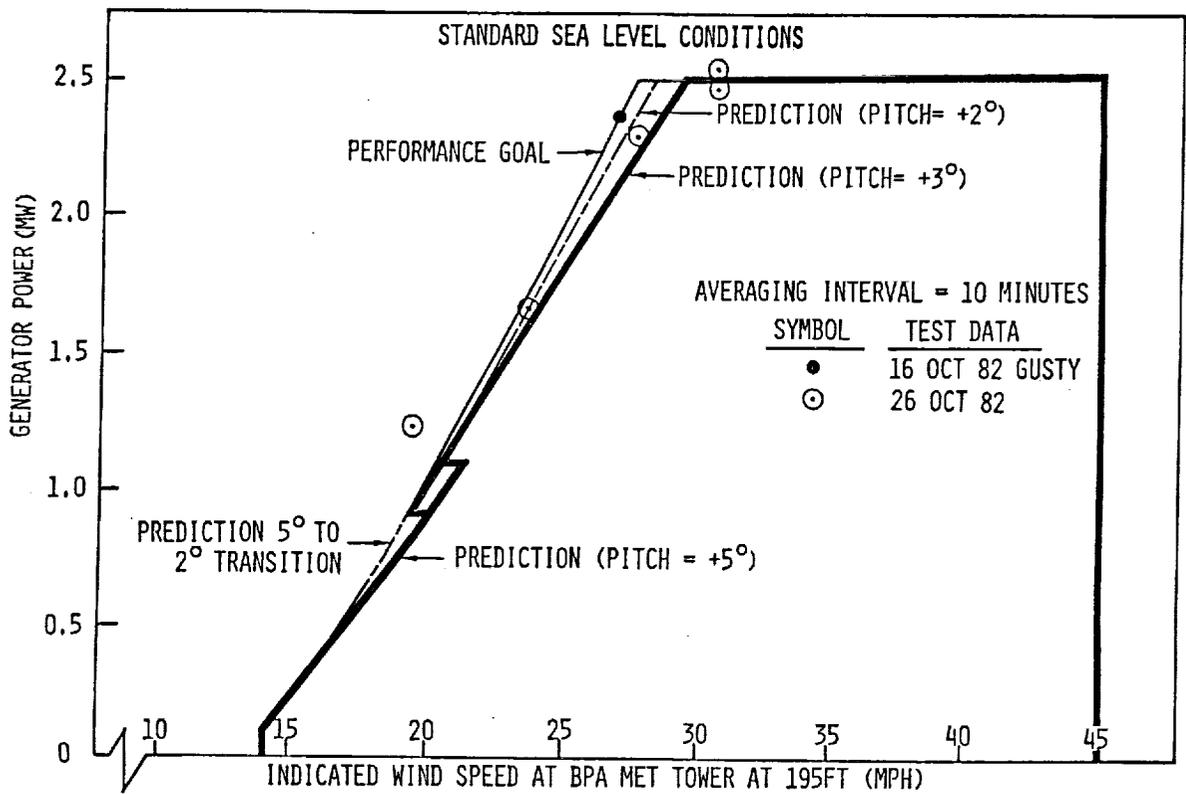


Figure 10 - WTS#2 Performance Data, October 1982

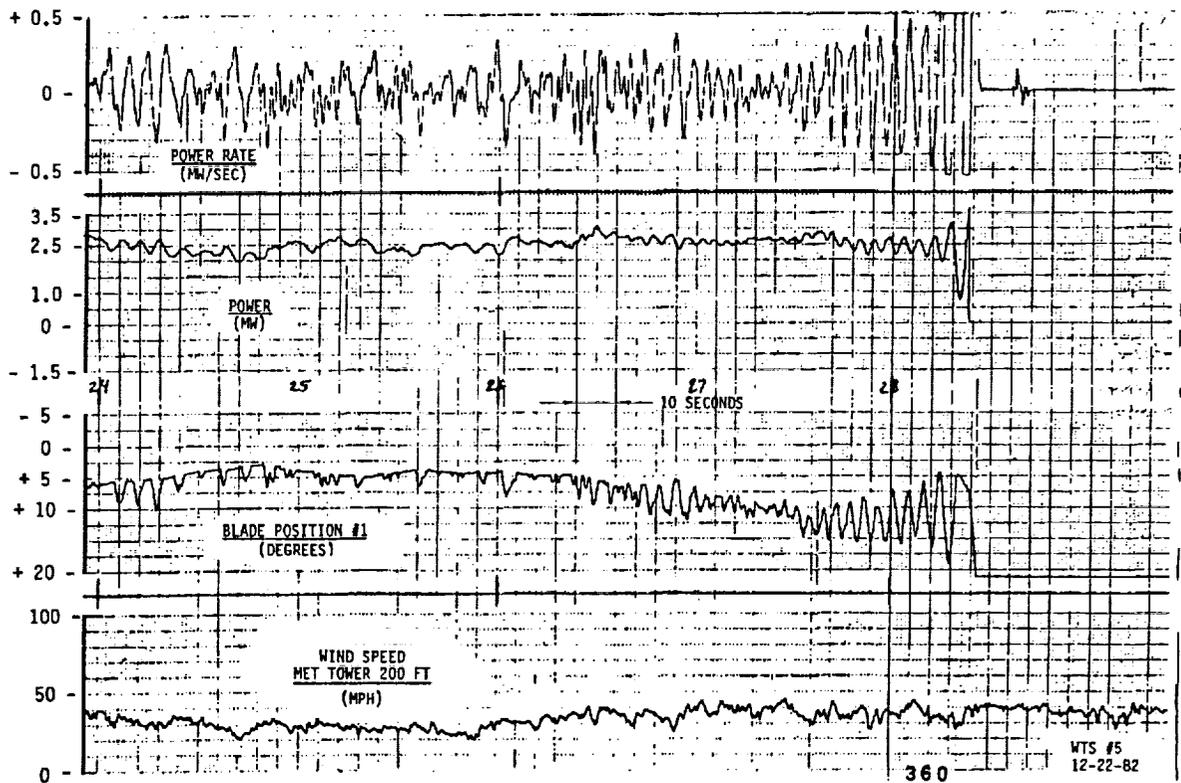


Figure 11 - WTS#5 Divergent Oscillation in High Winds, December 22, 1982

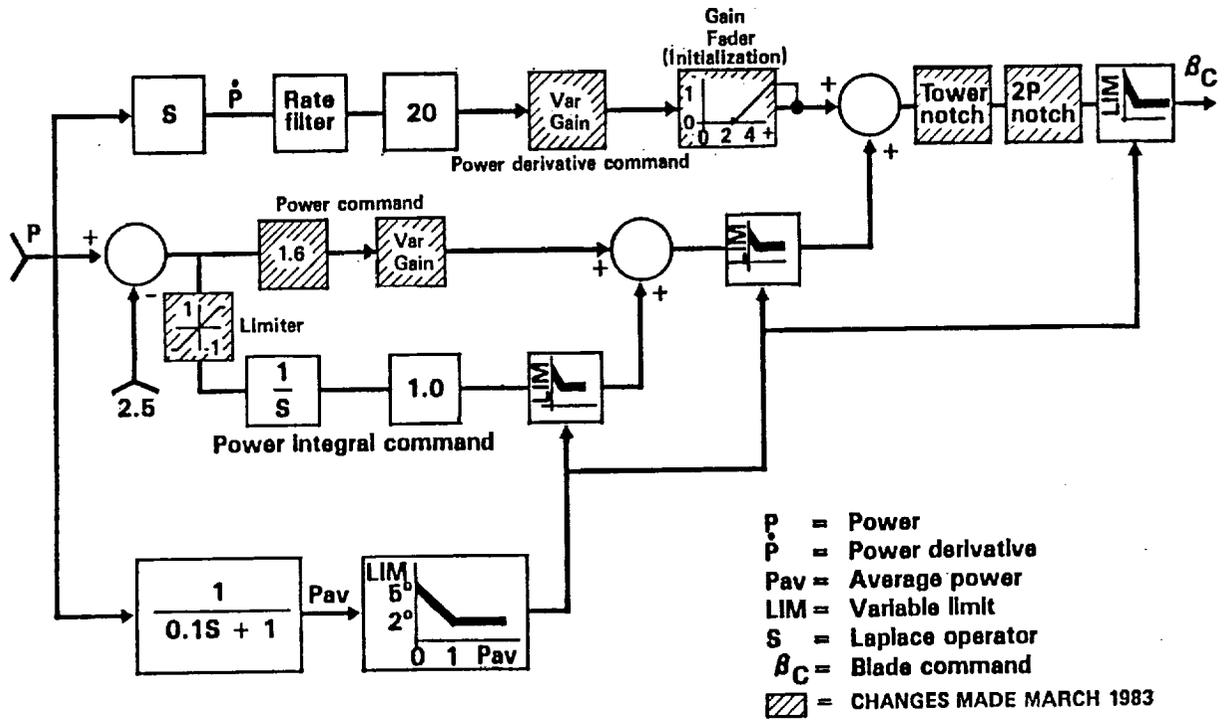


Figure 12 - Modified New Control System Functional Diagram

