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Wind Turbine Generator Interaction With Conventional Diesel Generators On Block Island, Rhode Island

Volume II—Data Analysis

V. F. Wilreker, P. H. Stiller
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Advanced Systems Technology
Westinghouse Electric Corporation

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ABS:  Assessing the performance of a MOD-OA horizontal axis wind turbine
      connected to an isolated diesel utility, a comprehensive data measurement
      program was conducted on the Block Island Power Company installation on
      Block Island, Rhode Island. The detailed results of that program focusing
      on three principal areas of (1) fuel displacement (savings), (2) dynamic
      interaction between the diesel utility and the wind turbine, (3) effects
      of three models of wind turbine reactive power control are presented. The
      approximate two month duration of the data acquisition program conducted
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FOREWORD

The United States Department of Energy sponsors -- and the National Aeronautics and Space Administration, Lewis Research Center manages -- the technological development of large horizontal axis wind turbines for the generation of electricity on utility networks. The potential fuel savings afforded by wind turbine use and the dynamic interaction of a wind turbine with a utility system are of particular interest. The goals of this study are to quantify fuel savings, determine the dynamic effects and evaluate three modes of volt-ampere regulation of the MOD-OA 150 kW wind turbine generator in operation on Block Island, Rhode Island.

This report presents an analysis of data collected during the winter months of 1982. The high level of wind power penetration over this period was the most severe of the four sites. Even so, the measured disturbance and interactive effects were of an acceptable level. The findings of this study are deemed to be valuable in providing a benchmark for predicting performance on future installations.

1. INTRODUCTION

This is the final report of a project managed by the National Aeronautics and Space Administration, Lewis Research Center (NASA-LeRC), and performed by Westinghouse Electric Corporation. The study was funded by the United States Department of Energy (DOE).

The objectives of this 12-month project were to investigate and quantify the fuel displacement and the dynamic performance associated with operating the experimental 150-kW MOD-OA wind turbine generator (WTG) on the isolated diesel generation system of the Block Island Power Company (BIPCO), Block Island, Rhode Island. The project included instrumentation specification, instrumentation installation, and data analysis.

1.1 Objectives of the Report

The objectives of this study were to determine:

- The energy interaction and fuel savings that resulted from operating the experimental MOD-OA 150 kW wind turbine generator on the isolated diesel generation system at Block Island, Rhode Island.

- The dynamic interaction between the wind turbine generator and the Block Island Power System.

- The effect of using three modes of wind turbine generator volt-ampere regulation on the Block Island Power System.

This report is primarily concerned with the interaction of the wind turbine generator with the BIPCO System.

1.2 The Plan of the Report

Section 2 contains a complete summary of the project's objectives and its results.

Section 3 describes the Block Island Power System and discusses the instrumentation installed for the study. This section describes the configuration of Block Island's generation to meet the diversity of summer and winter load. The total system winter load characteristics are presented.

Sections 4 and 5 comprise the major technical sections of the report. Section 4 describes the energy interaction and fuel savings associated with use of the MOD-OA wind turbine generator, and Section 5 describes the dynamic interaction between the wind turbine generator and the Block Island Power System. Each of these sections presents data collected, the analysis performed, and conclusions.

Section 6 describes the behavior of the wind turbine generator as it is operated in three modes of volt-ampere regulation. The three modes are: constant VAR output, constant power factor output, and voltage regulation.

1.3 The Project Team

To perform this project, the Lewis Research Center assembled a team with expertise in the required areas of study. The members of the team and their expertise are listed below:

Westinghouse Electric Corporation, Pittsburgh, PA

- Special Services Division, Greentree, PA
  - MOD-OA Support Services Contractor

- Advanced Systems Technology, Pittsburgh, PA
  - Diesel instrumentation
  - Data reduction
  - Data analysis
  - Reporting

- Engineering Services, Framingham, MA
  - Consulting
  - Instrumentation installation

Fairchild Weston Systems, Wheaton, MD
- Data recording system
- Data reduction

Block Island Power Company, Block Island, Rhode Island
- MOD-OA operation
- Instrumentation installation
- Data retrieval and collection

Lewis Research Center
- Project management
- Digital tape processing
- Technical review

1.4 Acknowledgement

Westinghouse would particularly like to acknowledge the efforts of F. Renz and M. Slate of the Block Island Power Systems Company for their invaluable assistance in installing the instrumentation, and their promptness in data retrieval and collection. In addition, we wish to thank the NASA-LeRC and DOE review team and their consultants for their assistance in reviewing this report.

2. SUMMARY

The utility industry has shown considerable interest in the use of renewable energy resources to meet the ever-increasing energy needs of the United States. Of particular interest to utilities is the integration of these new technologies into existing systems. Recent specific concerns have centered about the interaction of wind turbine generators with a utility system. NASA-LeRC and Westinghouse Advanced Systems Technology developed a three-part study to investigate and quantify this phenomenon. This study addressed fuel displacement, dynamic interaction, and three modes of volt-ampere regulation of the wind turbine.

2.1 Fuel Displacement Summary

The objective of the fuel displacement analysis was to determine the amount of diesel fuel displaced by the MOD-OA wind turbine generator on Block Island.

The 150-kW wind turbine designated MOD-OA by DOE was typically operated in parallel with two diesel generators. The system load during the two-month winter test period varied from 250 kW to 550 kW.

A complete instrumentation and data recording package was installed on three Block Island Power Company (BIPCO) diesel generators to monitor fuel flow rate, throttle position, and various electrical parameters, including generator power output. Important characteristics of the BIPCO system are summarized in Table 2-1.

Table 2-1

BIPCO Generation and Peak Load

Peak Load (Summer, 1981)		1800 kW
(Winter, 1981)		450 kW
Active Generation Capacity (Summer)	unit #9	400 kW
	#11	1140 kW
	#12	1000 kW
(Winter)	unit #8	225 kW
	#9	400 kW
	#10	500 kW
System Heat Rate (avg. 5 years)		17,600 Btu/kWh
Fuel		No. 2 fuel oil

During the test period, unit #9 or unit #10 maintained system frequency with a speed governor and controlled bus voltage with an active voltage regulator. Unit #8 was operated with a constant throttle position. Changes in wind turbine power output were compensated by the frequency controlling unit.

Under load frequency control, the throttle of unit #9 or #10 moved continuously to maintain system frequency.

Input/output curves were developed for each unit by measuring fuel input for various levels of constant power output while the unit was base loaded.

Consideration was given to four factors that might influence diesel fuel consumption during parallel operation:

1) gross wind turbine output
2) wind turbine auxiliaries
3) reduced diesel efficiency due to reduced diesel load
4) increased throttle activity

Energy Interaction and Fuel Displacement Summary

- The rate of fuel displacement by the experimental MOD-OA wind turbine generator on Block Island is equal to the incremental fuel consumption rate of the diesel unit on load frequency control.

- Diesel engine throttle activity does not significantly influence fuel consumption.

- The MOD-OA wind turbine on Block Island, displaced 25,700 lbs. of the diesel fuel during the test period, representing a reduction in fuel consumption of 6.7% while generating 10.7% of the total electrical energy.

2.2 Dynamic Interaction Summary

The objective of the dynamic interaction investigation was to quantify any increased disturbances to the Block Island power system resulting from connection of the MOD-OA. The potential dynamic interactions have been discussed in the literature and can be classified into four categories:

- Power and voltage transients due to the startup and shutdown sequence
- Power pulses as each blade passes through the tower wind shadow
- Power fluctuations due to wind gusts during fixed pitch control
- Power fluctuations due to wind gusts during variable pitch control

During the three month study period, the strip chart record revealed dynamic interactions from each of the four expected categories.

For the period of installation from mid 1979 to June 1982 of the Block Island MOD-OA wind turbine, there were over 8500 hours of successful synchronous operation and approximately 4300 start-stop cycles during which voltage fluctuations were not noticeable to customers.

The Block Island power system has a response to load changes which causes the system frequency to swing for one or two cycles at a rate of 0.9 rad/s to 1 rad/s (6 to 7 sec. period).

During startup and shutdown, the effect of the connecting or disconnecting of the MOD-OA in the Block Island system is of the same magnitude as produced by normal load fluctuations.

The effect of the blades passing through the wind shadow of the tower resulted in a cyclic power variation at twice the rotor speed of 31.5 rpm. The resulting 6.6 rad/s power oscillation had a wide range of amplitudes, depending on wind condition and pitch cycle. The governor controlled diesel units reflect these wind shadow variations so that the actual load requirements are met. Although the power variation can be quite large, the effect on system frequency is negligible due to the wind shadow.

When the WTG is connected, the inherent natural frequency of the BIPCO system (i.e. 0.9-1. rad/s) is found to be amplified. The effect is less severe under fixed pitch operation than under variable pitch (constant average power) control. The 0.9 rad/s power oscillation has been produced with amplitudes occasionally exceeding 100 kW peak-to-peak. The magnitude of the corresponding system frequency oscillation reaches 2 Hz peak-to-peak.

Analysis of the actual pitch control response during the 0.9 rad/s oscillation revealed an inconsistency with the expected response based on the programmed integral-plus-proportional pitch control and the hydraulic actuator response. The expected pitch response to a 0.9 rad/s variation in output power calls for the blade pitch to lag the power error (P_{max} - P_{wtg}) by 80 degrees. The measured response was found to be lagging the power error signal by 110 to 130 degrees. The exact cause of this additional phase lag is not known from the available pitch data or from simulation of the microprocessor controller.

The measured phase and amplitude data was used to infer an auxiliary transfer function that in conjunction with the known transfer function of the blade pitch loop matched the measured data at .9 rad/s. Then the WTG and diesel generator dynamics were simplified to produce a model allowing analysis of the .9 rad/s oscillation mode. The power and frequency transient responses produced by this model to a step in wind torque agree with the actual measurement. It is then shown that modifying the proportional integral constants of the microprocessor blade pitch controller yield greatly improved damping of the .9 rad/s mode.

2.3 MOD-OA Volt-Ampere Regulation Summary

The objective of the volt-ampere regulation study was to evaluate the three modes of operation of the MOD-OA voltage regulator. The three modes of regulation were constant reactive power, constant power factor, and constant voltage control.

Normal operating procedure on Block Island called for constant reactive power control at a setting of 60 kVAR. Recorded data showed that the MOD-OA wind turbine contributed nearly constant 60 kVAR under typical conditions and did not interfere with voltage control by the diesel unit #9. It has the desirable property of providing a non-fluctuating source of vars to the system while maintaining adequate synchronizing torque of the WTG. As such it is deemed to be marginally the most desirable system of the three. While operating in constant reactive power control during the month of February, 1982, the MOD-OA wind turbine operated for 396 hours and generated 26 MWh of electrical energy.

Under constant power factor control the reactive power output followed the real power output. At a setting of 0.85 pf, the ratio of reactive to real power was 0.62. This type of control has the property of making the WTG appear to the constant voltage controlled diesel generations as a fluctuating inductive load thereby increasing the excitation demand on these diesel units. However, it has the desirable characteristics of creating the highest synchronizing torque because vars and power are in phase. During March, 1982, the MOD-0A wind turbine was operated for 443 hours in this mode and generated 32.4 MWh of electrical energy.

A constant voltage control test was conducted in which the voltage droop setting was varied from 5% to 0%. In this mode, the MOD-0A voltage regulator took over the major share of regulating voltage fluctuations and proved to have a faster response than the voltage-regulating diesel -- unit #10. The characteristics of constant voltage control in terms of synchronizing torque is the least desirable of the three methods since vars and power fluctuations tend to be out of phase.

A simulation model comprising the detailed transfer functions of each of the three methods of regulation and a D-Q axis representation of the wind alternator was formulated. Transient responses to a step in wind torque were generated to evaluate voltage and frequency behavior. From simulation model results and from the measured data, it is demonstrated that the MOD-0A WTG on the BIPCO system will successfully operate on all three modes of excitation (volt-ampere) regulation.

3. BLOCK ISLAND POWER COMPANY

In this section, a description of the Block Island Power Company (BIPCO) is given. The winter load characteristics and the configuration of the generation in winter are described. The section concludes with a summary of the wind turbine and diesel study instrumentation installed for the fuel consumption and dynamic interaction tests.

3.1 The Power System of Block Island

BIPCO is an investor-owned electric utility serving the entire island of Block Island, Rhode Island. As the island is some 10 miles offshore, the utility is not electrically interconnected to any other utility. The utility has approximately 900 residential and commercial customers served by 53 miles of 2.4 kV distribution. According to 1979 figures, BIPCO's total electric energy sales were approximately 3300 MWh. Total diesel generation capacity is 4265 kW.

3.2 Winter Load Characteristics

The major industry on Block Island is tourism. During the summer months the population increases from about 600 permanent residents to 5,000. The full-time winter population is engaged mainly in maintenance and construction for the summer season, some fishing, and support services. There is no heavy industry on the island, so the electrical load is residential and commercial.

Figure 3-1 shows a plot of system kilowatt demand vs. time for a typical winter week. The load varied from 250 kW to 550 kW during the test period. The daily load shape was typical for a residential and commercial community. A small peak occurred at approximately 8:00 a.m. each morning, followed by a larger peak in the late afternoon between 5:00 p.m. and 7:00 p.m. The weekly load shape has two peaks on both Friday and Saturday evenings.

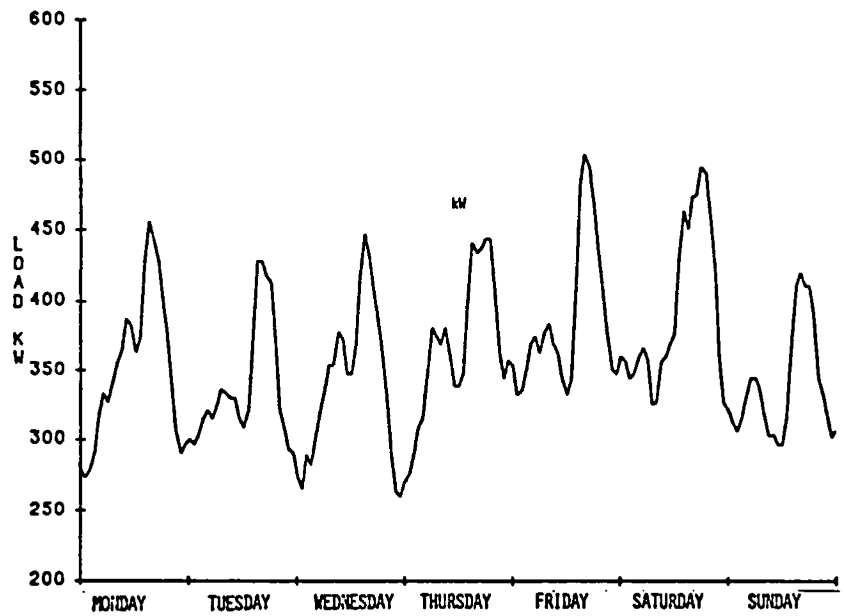


Figure 3-1. Winter BIPCO Power Demand for Week of February 22, 1982.

Figure 3-2 shows a plot of reactive demand (lagging) and Figure 3-3 shows kVA demand for for the same period of time shown in Figure 3-1. As can be seen, the reactive demand has a less distinct daily and weekly load shape. During the non-tourism season, the fixed reactive load in comparison to the kilowatt load is high. The base reactive demand was approximately 400 kVAR. System power factor was below 70% for most of the week shown.

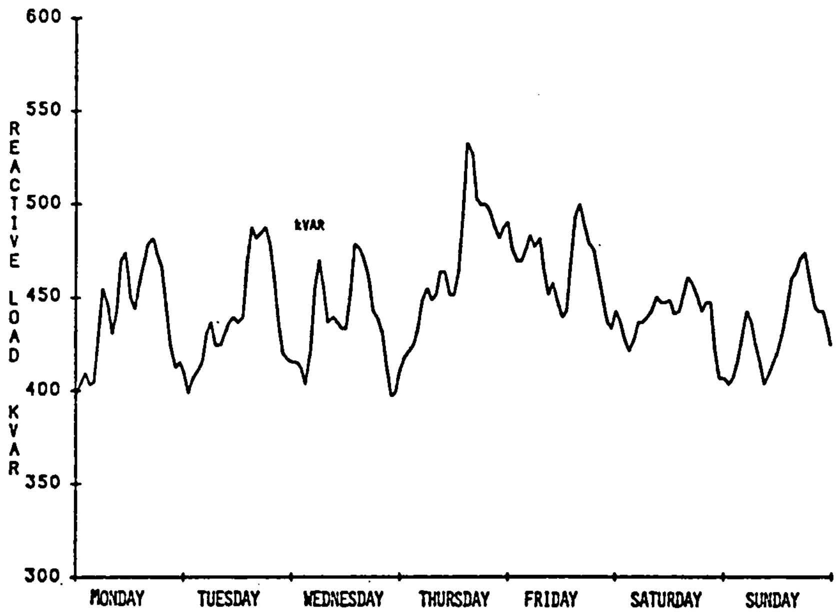


Figure 3.2. Winter BIPCO Reactive Demand for Week of February 22, 1982.

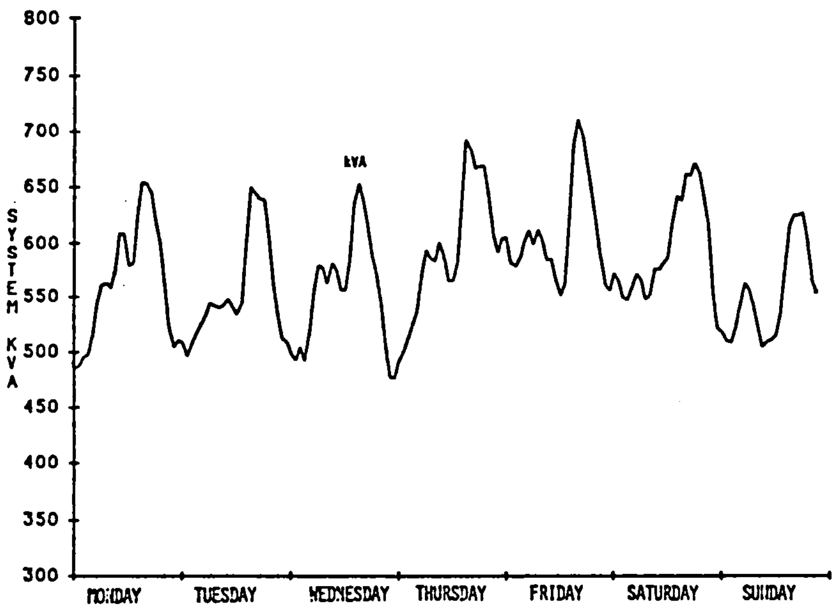


Figure 3.3. Winter BIPCO KVA Demand for Week of February 22, 1982.

3.3 BIPCO Winter Generation Configuration

The electrical one-line diagram (Figure 3-4) shows the diesel generation configuration of the Block Island Power Company and the electrical connection of the MOD-OA 150 kW wind turbine generator. Table 3-1 shows pertinent data on those generators that were most often used throughout the year.

Table 3-1

Diesel Generator Specification Data

Unit #	Make	Rating	Regulator/Governor
8	Caterpillar	225 kW, 281 kVA 2.4/4.16 kV, 1200 rpm	Westinghouse Silverstat/ Woodward UG8
9	Fairbanks-Morse	400 kW, 500 kVA 2.4/4.16 kV, 1200 rpm	Westinghouse Silverstat/ Woodward UG8
10	Fairbanks-Morse	500 kW, 625 kVA 2.4/4.16 kV, 1200 rpm	Westinghouse Silverstat/ Woodward UG8
11	Fairbanks-Morse	1140 kW, 1424 kVA 2.4/4.16 kV, 720 rpm	Westinghouse Silverstat/ Woodward UG8
12	Fairbanks-Morse	1000 kW, 1250 kVA 2.4/4.16 kV, 720 rpm	Westinghouse Silverstat/ Woodward UG8

In winter months the Block Island Power Company usually operated two generators to maintain system load. Typically, unit #8 was used with unit #9 or unit #10. Unit #8 was run with no speed or voltage regulation. Unit #9 or unit #10 maintained system frequency with a Woodward speed governor, and also controlled bus voltage with an active voltage regulator. All voltage regulation (VAR support) was supplied by the on-line generation as there were no fixed capacitors installed on the Block Island Power System. Figures 3-5, 3-6, and 3-7 illustrate the generation for diesel units #8 and #9 plus the MOD-OA wind turbine for the week of February 22, 1982.

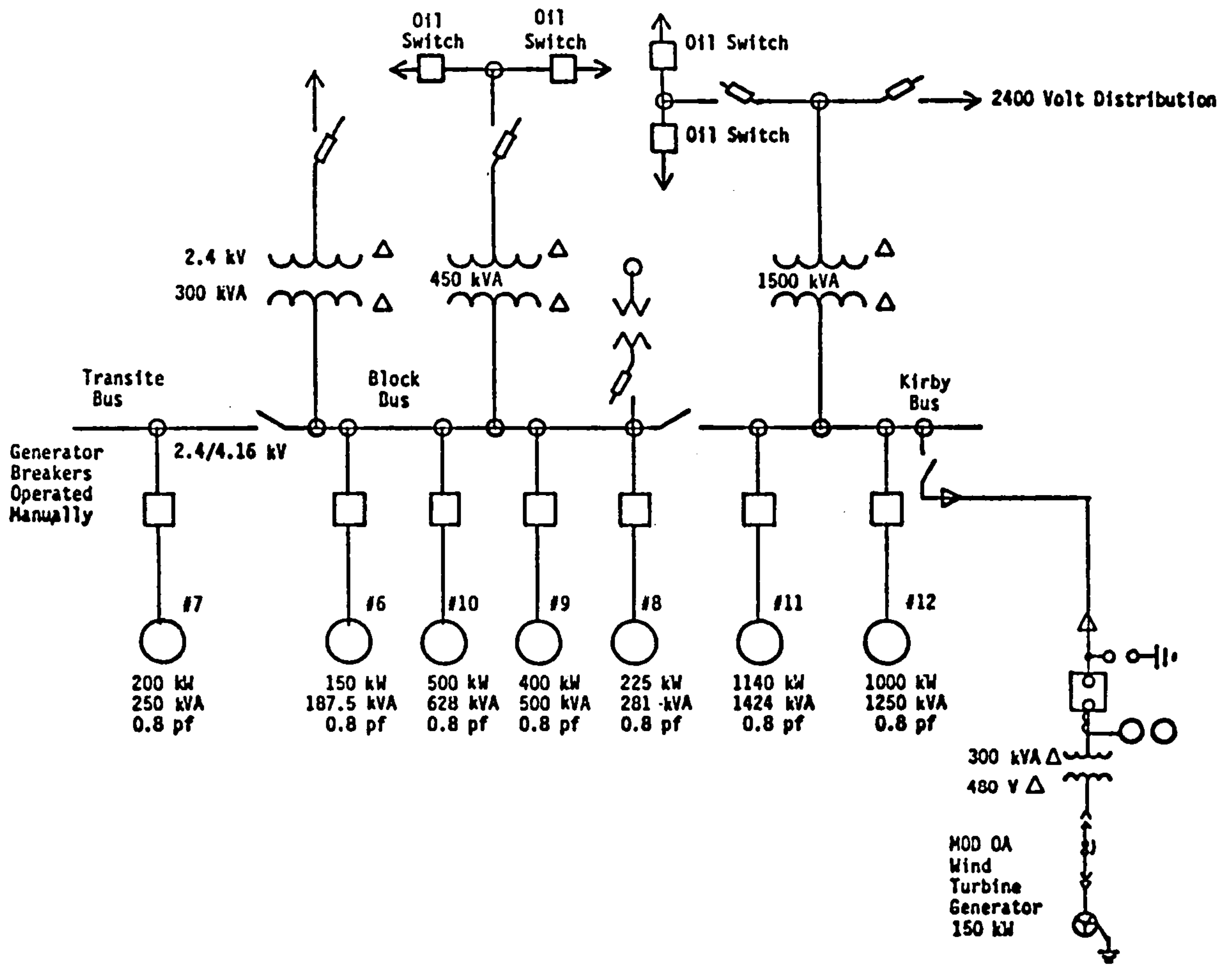


Figure 3-4. Block Island Power Company Generation System and the NASA MOD-OA Wind Turbine Generator.

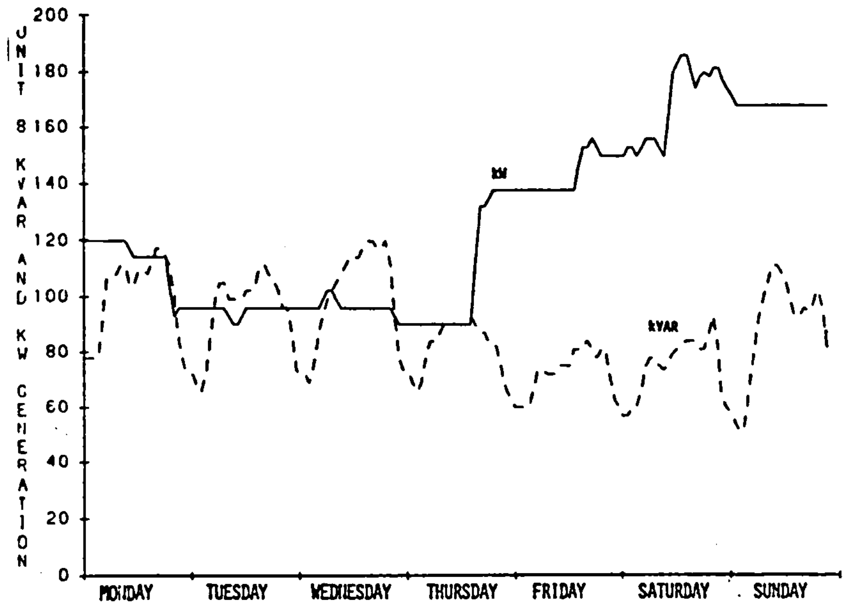


Figure 3-5. Unit #8 Generation for Week of February 22, 1982

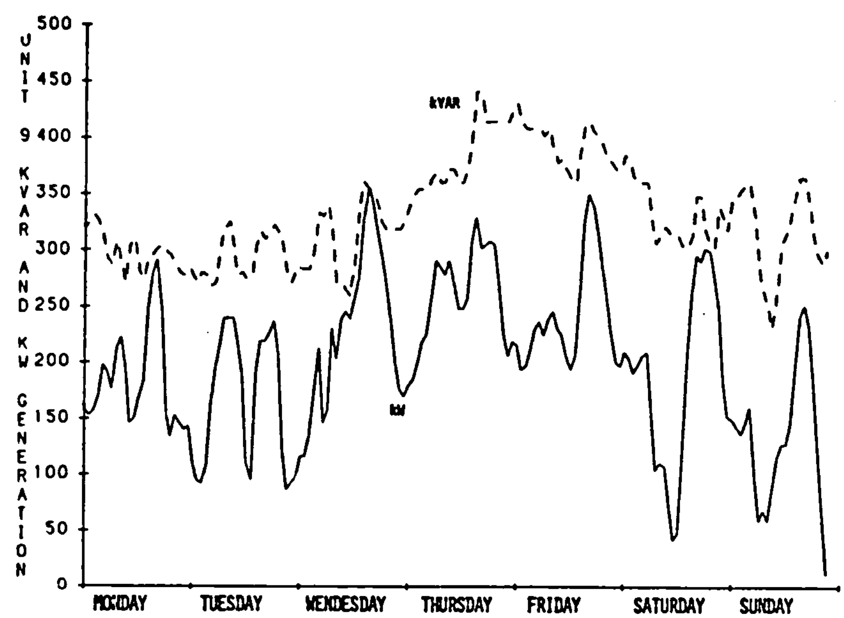


Figure 3-6. Unit #9 Generation for Week of February 22, 1982

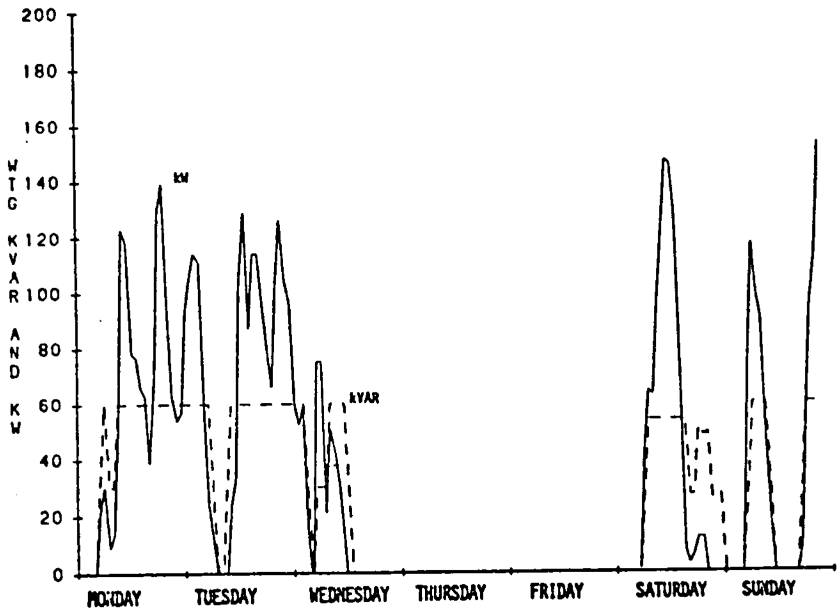


Figure 3-7. MOD-OA 150 kW Wind Turbine Generation For Week of February 22, 1982.

3.4 Operational Considerations

The MOD-OA wind turbines were designed for 200 kW output. On the winter configured BIPCO system, this would have produced a very high penetration. Consequently, the Block Island MOD-OA installation had a manually adjustable output setpoint. This was the only MOD-OA installation to incorporate such a feature.

In October, 1980, the MOD-OA rating was modified from 200 kW at 40 rpm to 150 kW at 31.5 rpm. This was done to maximize energy capture, because this change in speed ratio allowed the MOD-OA to deliver power for longer periods of time in high and/or gusting wind condtions. During the test period several wind turbine blade strain shutdowns occurred in February of 1982. Operation of the wind turbine with the output set considerably below rated in combination with gusty winds resulted in flapwise blade loads in excess of design values. At this time, NASA-LeRC continued to monitor blade loads for the Block Island installation and directed the wind turbine to be operated only at the 150-kW set point.

The high wind turbine penetration at Block Island prompted other considerations. In early spring as warmer weather approaches, the system demand during off hours fell to approximately 275 kW. With the wind turbine operating at 150 kW, one of the diesels on Block Island would operate at idle or zero load. If a diesel is operated at such low power levels for too long, the low engine temperature risks engine damage or fire due to oil accumulation in the exhaust stack. To avoid these problems, the wind turbine was shut down from midnight to 8 AM.

The Block Island MOD-OA wind turbine was not operated during the summer of 1982. It was felt that sufficient data had been collected and that light winds during the summer months would provide little power variability and minimal penetration, resulting in a poor return for the investment required for further testing. It was also felt that the BIPCO system had many operational constraints that were unique and not representative of typical utilities.

3.5 Instrumentation to Study The MOD-OA Utility Interaction

Three BIPCO diesel generators (units #8, #9, and #10) and the MOD-OA wind turbine were instrumented for unattended data collection for the period February through April, 1982. All data were recorded on magnetic tape using the DOE/NASA Engineering Data Acquisition System shown in Figure 3-8. This acquisition system also included strip chart display capability for selected channels. Parameters measured and recorded are summarized in Table 3-2 and Table 3-3. Tapes and strip charts were then returned from the field for cataloging and analysis.

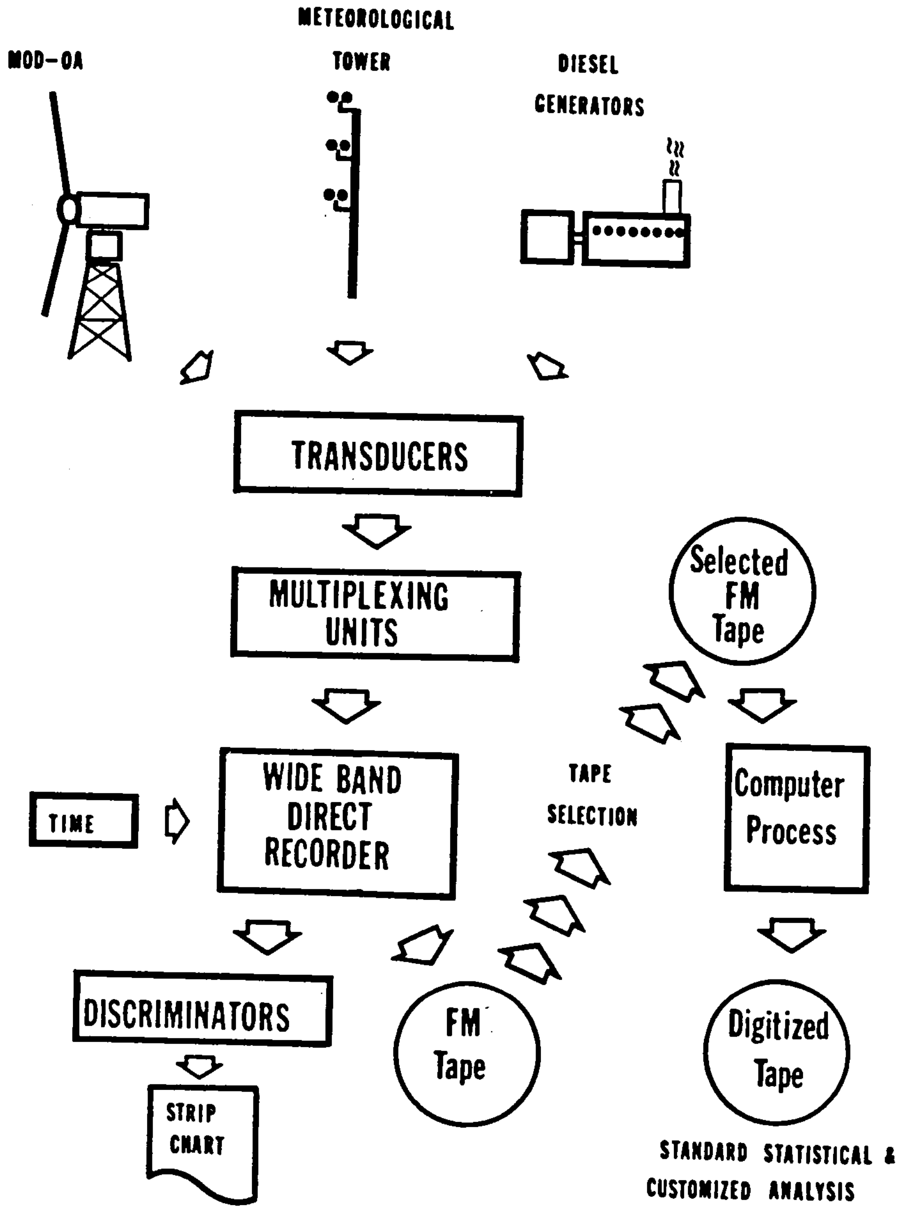


Figure 3-8. DOE/NASA Engineering Data Acquisition System.

Table 3-2

Parameters Measured and Recorded for the Wind Turbine

Parameter	Units
real power	kilowatts
reactive power	kilovars
phase current	amperes
phase potential	volts
electrical frequency	hertz
blade pitch angle	degrees
rotational speed	rpm
nacelle direction	degrees
yaw torque	N-m
yaw error	degrees
blade bending moment	N-m
wind speed at hub	m/sec
wind speed at tower (30', 100', 150')	m/sec

Table 3-3

Parameters Measured and Recorded for A Typical Diesel Generator

Parameter	Units
real power	kilowatts
reactive power	kilovars
phase current	amperes
line potential	volts
field current	amperes (dc)
field potential	volts (dc)
electrical frequency	hertz
fuel mass flowrate	lbs/hour
diesel throttle position	degrees

(Details of the instrumentation are included in Appendix A.)

4. ENERGY CONVERSION CHARACTERISTICS

One objective of the study was to quantify the influence of the wind turbine on diesel fuel consumption by determining the amount of fuel displaced by wind energy. To meet this objective, a complete instrumentation and data recording package was installed on three BIPCO diesel generators to monitor fuel flow rate, throttle position, and various electrical parameters including generator power output. Data from the diesel instrumentation and data from the wind turbine were simultaneously recorded to study the influence of the wind turbine on fuel consumption.

4.1 Fuel Displacement of the Wind Turbine Generator

Four factors were suspected of influencing diesel fuel consumption during parallel operation:

1) gross wind turbine output
2) wind turbine auxiliaries
3) reduced diesel efficiency due to reduced diesel load
4) increased throttle activity

The interrelationship of these factors is illustrated in Figure 4-1.

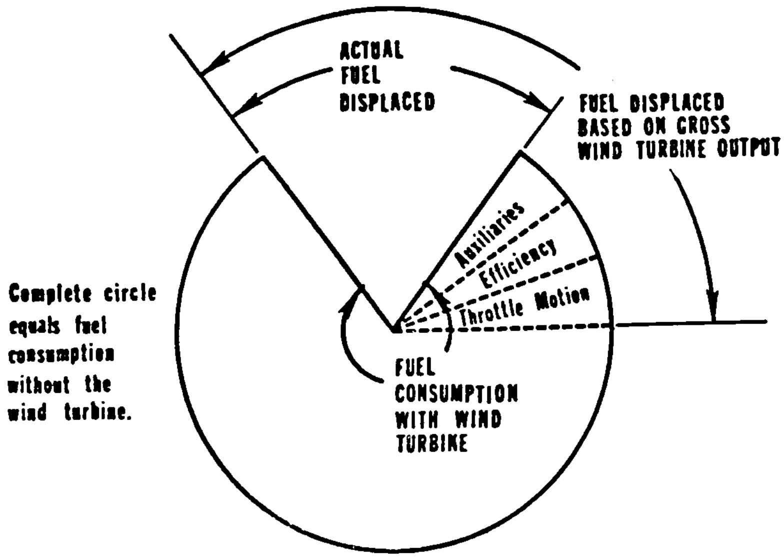


Figure 4-1. Fuel Displaced by Wind Turbine

Gross wind turbine output reduces diesel fuel consumption by contributing electrical energy without using fuel. Wind turbine auxiliaries -- including controls, instrumentation, heating and air conditioning -- increase diesel fuel consumption by using electrical energy that would otherwise serve utility customers.

Diesel efficiency under steady-state conditions is primarily a function of load. Diesel engines are more efficient at higher loads. Increased wind generation drives diesel load down, causing the diesel to operate at lower efficiency, which suggests an increase in apparent fuel consumption as shown in Figure 4-1.

Wind gusts cause rapid wind turbine output fluctuations which are compensated by diesel output changes to hold constant frequency. Rapid or extreme diesel throttle variations were suspected of increasing fuel consumption. Throttle motion is also illustrated in Figure 4-1.

Overall influence of the wind turbine on fuel consumption is determined by quantifying the four factors to establish net displaced fuel.

4.2 Fuel Consumption of Block Island Diesels

Procedure

Data were continuously collected on diesel and wind turbine operation for two months. The information was automatically recorded. The only manual interruptions were strip chart and magnetic tape changes for a few minutes every three days. Selected channels were recorded on the strip chart for monitoring purposes. A complete analog record was made on magnetic tape. A typical strip chart record is shown in Figure 4-2.

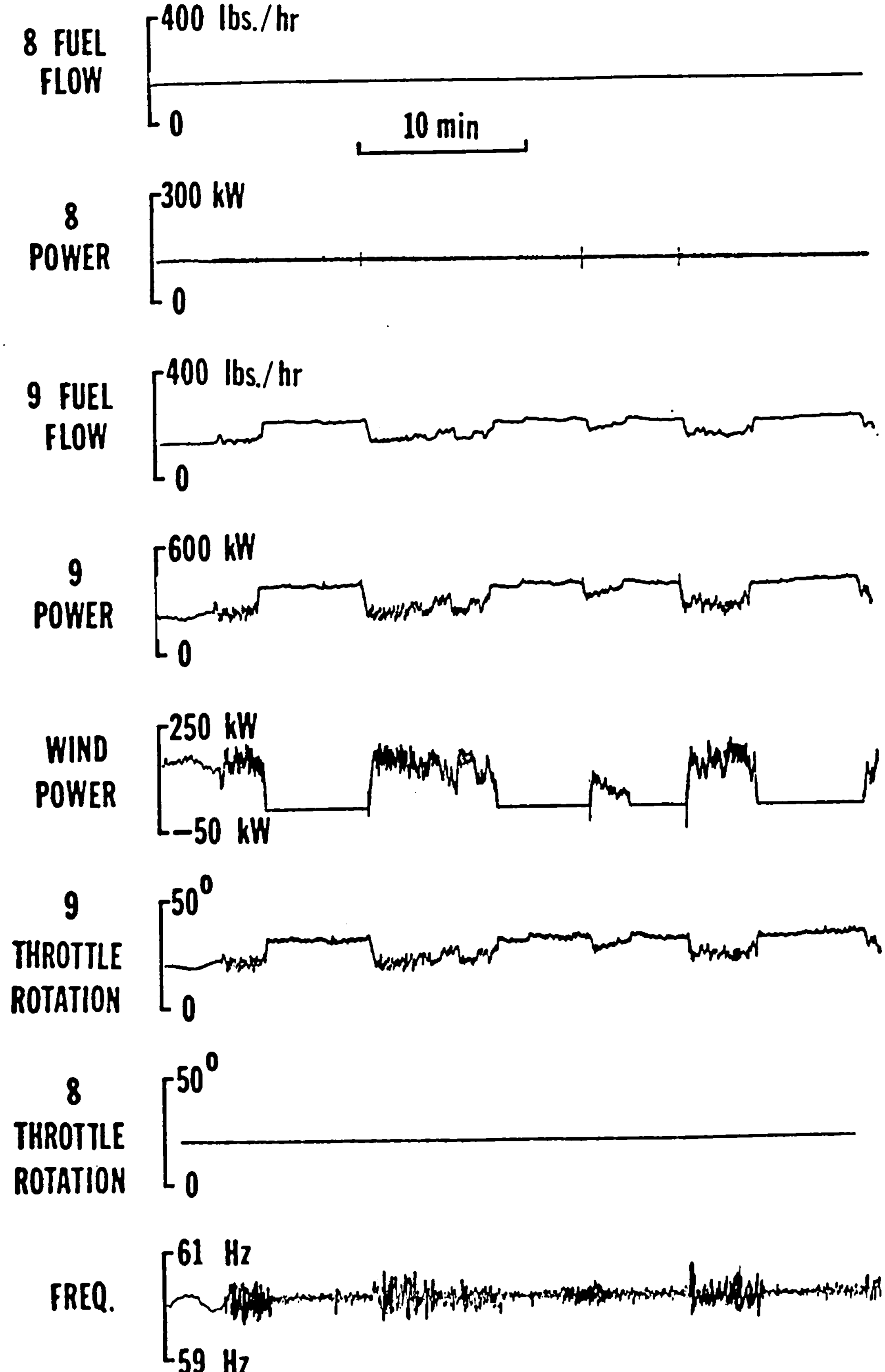


Figure 4-2. Sample Strip Chart Record 1:00 PM to 1:30 PM 2/6/8

Table 4-1

Typical Winter Generation Unit Loads

		Rating	Output Low Wind	Output High Wind
Diesel Unit	#8	225 kW	100 kW	100 kW
	#9	400	225	100
	#10	500	0	0
MOD-OA WTS		150	25	150
System Load			350	350

Unit #8 was run with constant throttle position (ungoverned), which results in constant power output. Unit #9 or #10 maintained system frequency with a speed governor and also controlled bus voltage with an active voltage regulator. Changes in wind turbine output were counteracted by unit #9 output. The MOD-OA experimental wind turbine was automatically controlled by a microprocessor to generate power to a preset limit as wind was available.

During the test period, BIPCO personnel cooperated by shifting responsibility for load frequency control to various diesel units to allow collection of operating data for each diesel in fixed-throttle and base-load operation. Under load-frequency control, the engine throttle moved continuously in order to maintain system frequency. The comparison of fixed-throttle data and frequency-control data was important because the influence of throttle activity on fuel consumption was one factor to be evaluated.

Analysis

The objective of this analysis was to determine the amount of diesel fuel displaced by the MOD-OA wind turbine on Block Island. The DOE/NASA Engineering Data Acquisition System (Figure 3-8) was used to collect a comprehensive data base capable of supporting several different analyses.

Diesel Unit Input/Output Characteristics

During the two-month testing period, three diesel units were operated by BIPCO. The input/output curve was developed for each unit by measuring fuel input for various constant levels of power output while the unit was base loaded. The input/output curve for each unit given in Figure 4-3 is based on fifteen minute average fuel flow and power output values sampled every half second. The locus of input/output points for each diesel can be described by a straight line. The input/output curve for each diesel was then converted to an efficiency curve by dividing output by input over the diesel operating range. The efficiency characteristic for each diesel is given in Figure 4-4.

Figure 4-3 and 4-4 present the same information, but do so in different ways. The efficiency curve of a diesel is derived from its input/output characteristic.

$$\text{Efficiency} = \frac{\text{kWh output}}{\text{fuel input}} \tag{4-1}$$

$$= \frac{\text{kWh output}}{\text{Idle fuel + fuel for kWh output}} \tag{4-2}$$

$$= \frac{\text{kWh output}}{\text{Time x Idle fuel flow + kWh x incremental fuel consumption}} \tag{4-3}$$

Idle fuel consumption (the fuel required to operate each diesel at zero electrical output), and incremental fuel consumption are the y-intercept and slope of the input/output line respectively in Figure 4-3. Idle fuel consumption and incremental fuel rate for each of the BIPCO winter diesels are listed in Table 4-2. Idle fuel consumption is that fuel required to overcome mechanical losses. It is the non-zero fuel consumption which causes the non-linearity of the efficiency curves of the diesels under test.

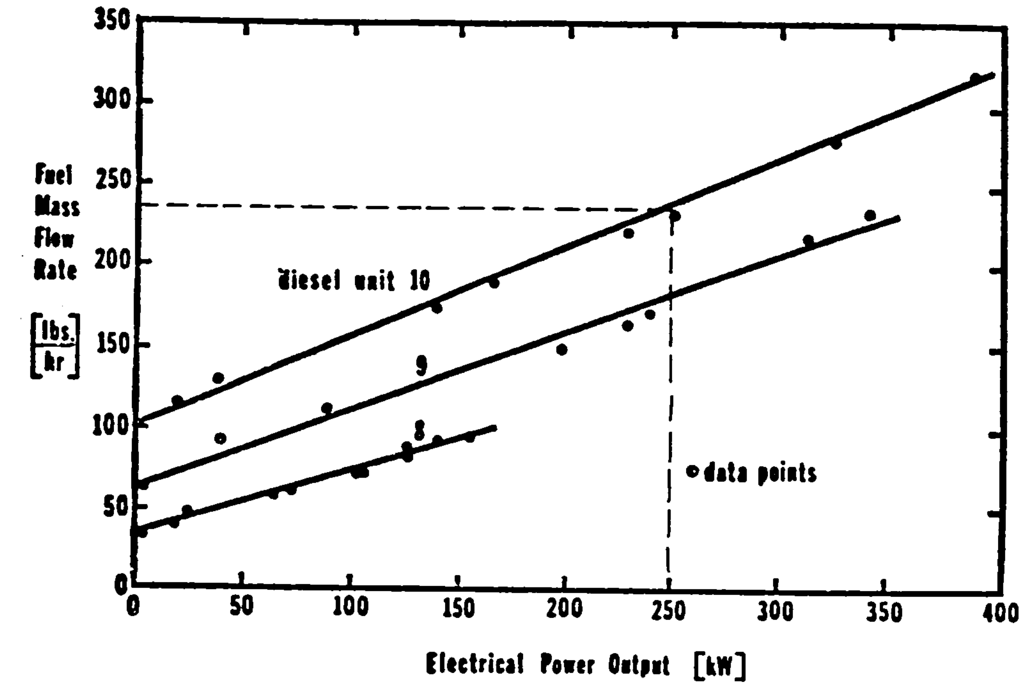


Figure 4-3. Diesel Input/Output Characteristics

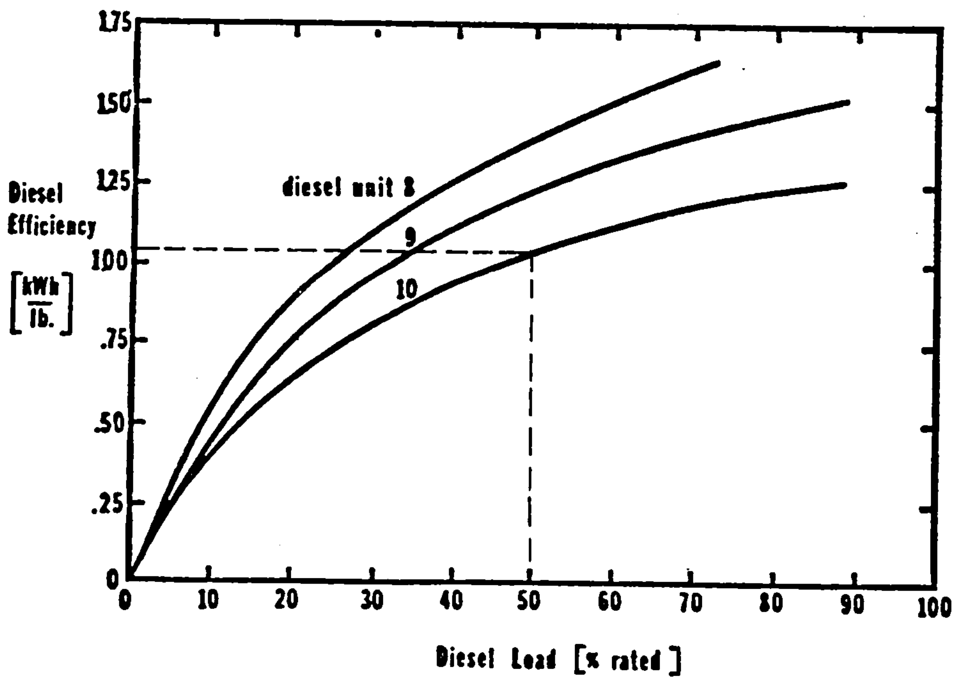


Figure 4-4. Diesel Efficiency Curves

The relationship of input/output and efficiency curves can be illustrated by an example. If unit #10, which is rated at 500 kW, has an electrical load of 250 kW, the fuel mass flow rate is 240 lbs/hr. The efficiency in kilowatt-hours per pound is equal to:

$$\frac{250 \text{ kW}}{240 \text{ lbs/hr}} = 1.04 \quad {}^{\text{kWh}}/_{\text{lb}} \tag{4-4}$$

The diesel load (250 kW) is 50 percent of the rated output (500 kW) for unit #10. From the curve in Figure 4-4 it can be seen that for a load, 50 percent of rated, the efficiency in kilowatt hours per pound of fuel is 1.04.

Table 4.2

Diesel Unit Incremental Rate and Idle Consumption

Unit #	Incremental Rate	Idle Fuel Consumption
8	0.43 lb. fuel/kWhr	31.7 lb/hr
9	0.49 lb. fuel/kWhr	62.9 lb/hr
10	0.57 lb. fuel/kWhr	100 lb/hr

Incremental Fuel Consumption

As the wind turbine increases its output, each kilowatt of wind generation replaces a kilowatt of diesel generation.

The system electrical load is exactly met by generation in order to maintain frequency. As the wind turbine increases its output, the diesel under frequency control is throttled back. Replacing the diesel output with wind turbine power is similar to reducing the system load. In both cases, the diesel output is reduced; however, reducing diesel output results in lowered diesel efficiency (Figure 4-4). It would appear that some decrease in fuel displacement might occur because the diesel operates at a lower efficiency. As has been demonstrated though, diesel efficiency curves and input/output characteristics are equivalent. Figure 4-3 shows that the incremental fuel consumption -- the slope of the input/output characteristic -- is constant for the diesels being studied. At any operating point above zero diesel output, reducing the output causes a proportionally constant reduction in fuel flow. Therefore, there is no fuel displacement reduction for operating at a lowered diesel efficiency.

The amount of displaced fuel can be found by multiplying the change in diesel output (equal to the net wind turbine output) by the incremental fuel consumption in pounds of fuel per kilowatt hour. The incremental fuel consumption and idle fuel flow are given in Table 4-2. For example, if unit #10 is operating under load frequency control, and the wind turbine has an output of 100 kW, the fuel displacement at the end of a 2-hour period is:

$$100 \text{ kW} \times 2 \text{ hrs.} \times 0.57 \text{ lb/kWh} = 114 \text{ lbs.} \qquad (4\text{-}5)$$

Diesel Throttle Motion

The diesel unit responsible for load-frequency control must continuously adjust power output to maintain electrical frequency. This is necessary because electrical load and wind turbine power output change continuously. The diesel speed governor moves the engine throttle to maintain frequency. In order to examine the effect of throttle motion on engine efficiency, "throttle activity" must be quantified.

Throttle position, in degrees of rotation, was continuously recorded for the diesel unit on load frequency control and converted to digital data with a 0.5 second interval between data points. Throttle activity was then quantified by computing total angular travel over a time interval and dividing by the interval of time. Since both directions of travel are taken as positive, the computed parameter becomes average throttle angular speed in degrees per second, thus providing a measure of throttle activity:

$$\text{Avg. Throttle Angular Speed} = \frac{\displaystyle\sum_{K = T_s}^{T_f - 0.5} \left| \Theta_K - \Theta_{K+1} \right|}{T_f - T_s} \qquad (4\text{-}6)$$

where: T_s = Initial time of interval

T_f = Final time of interval

Θ_K = Throttle position at time K

Θ_{K+1} = Next throttle position value after time K

0.5 = Time between data points

A 15-minute time period having high throttle activity was analyzed to determine fuel penalty as a result of throttle motion and the results were plotted in Figure 4-5. The relevant digital data for the analyzed period of 2:35 p.m. to 2:50 p.m., February 3, 1982, is plotted in Figures 4-6 through 4-9. The corresponding strip chart data is located in Appendix B, Figures B6 through B9. Average throttle speed (unit #9) was computed for forty-five 20-second intervals. The average fuel flow and diesel kilowatt output were calculated for the corresponding 20-second intervals. The predicted fuel flow for each 20-second interval was computed using incremental consumption, idle rate, and the average kilowatt output of unit #9 (Table 4-2). Computed values of flow were compared to measured values and the difference was plotted in Figure 4-5 as a percent of the computed fuel flow versus the average throttle angular speed. Figure 4-5 shows that throttle activity is not a significant factor in fuel displacement.

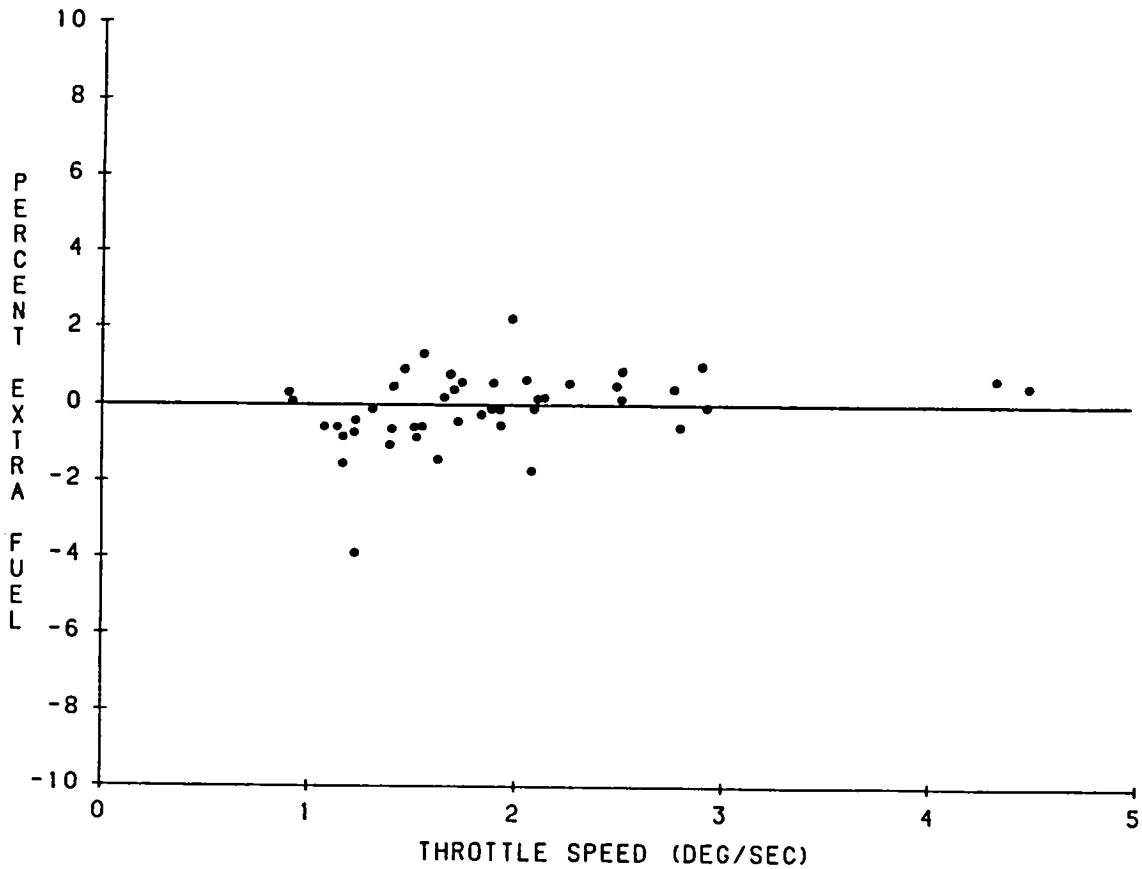


Figure 4-5. Throttle Motion vs. Extra Fuel

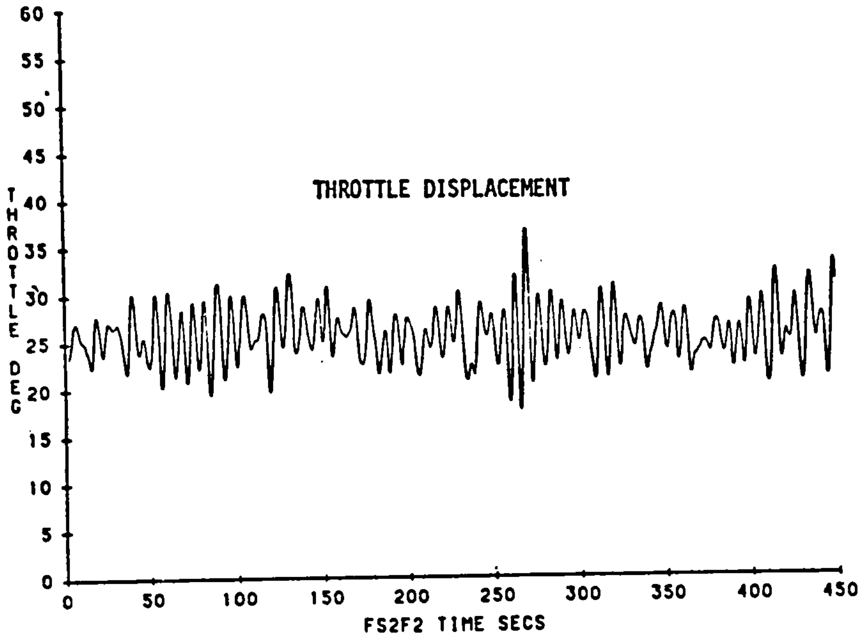


Figure 4-6. Unit #9 Throttle Displacement 0-450 Seconds

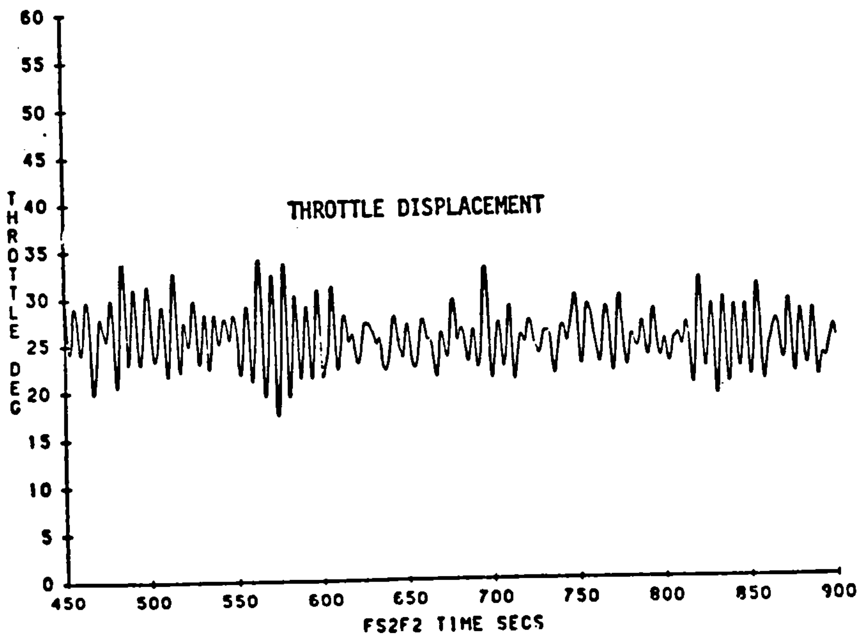


Figure 4-7. Unit #9 Throttle Displacement 450-900 Seconds

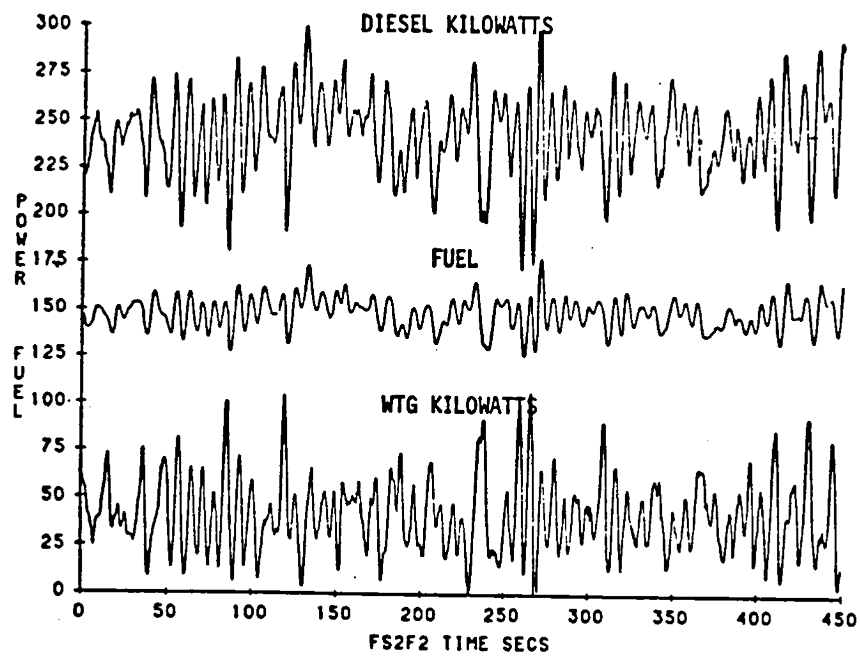


Figure 4-8. Unit #9 Fuel and Machine Output 0-450 Seconds

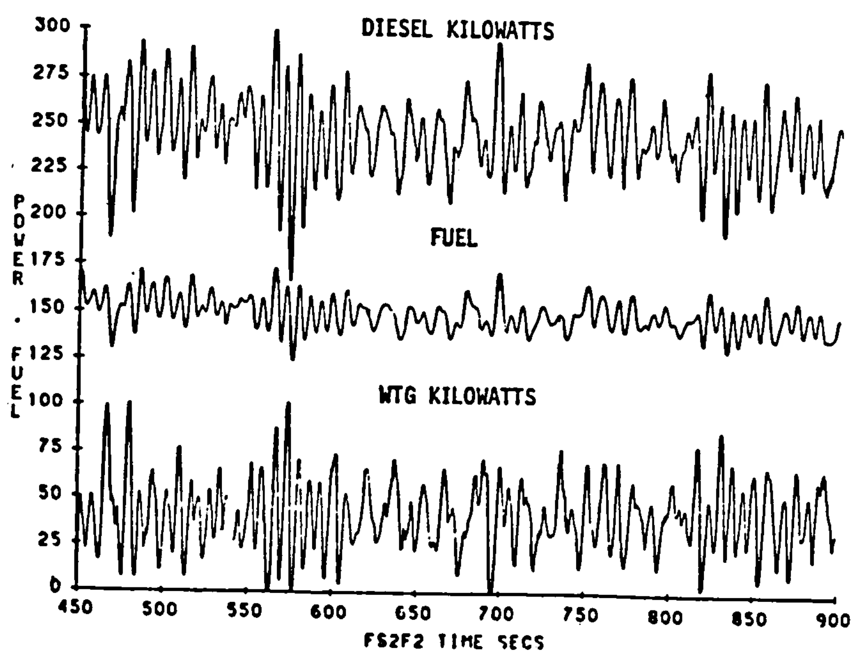


Figure 4-9. Unit #9 Fuel and Machine Output 450-900 Seconds

Results

The results of the fuel consumption analysis are summarized in Figure 4-10 for two examples corresponding to the unit loads for "low wind" and "high wind" of Table 4-1. Unit #8 is loaded to a constant 100 kW and unit #9 provides the balance. Fuel consumption reduction is shown for 25 kW and for 150 kW of net wind turbine output. Figure 4-10 does not show any effects of throttle motion or reduced diesel efficiency as these have been demonstrated as having no measurable effect on fuel displacement.

When unit #9 is under load-frequency control, each kilowatt hour of net wind generation displaces 0.49 lbs (0.067 gal.) of fuel which corresponds to the incremental fuel consumption rate for unit #9 (Table 4-2). When unit #9 is replaced by unit #10, each kilowatt hour of net wind generation displaces 0.57 lbs. (0.078 gal.) of fuel.

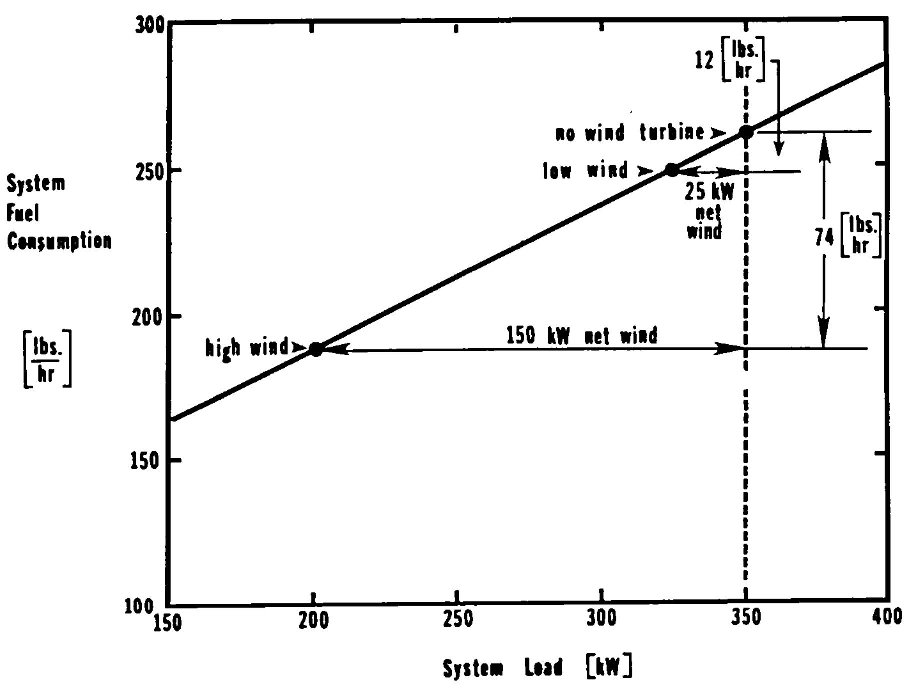


Figure 4-10. Fuel Displacement Results

Fuel displacement with the wind turbine is a function of unit dispatch. Fuel displacement can be maximized by operating the wind turbine in parallel with the diesel having the highest incremental fuel consumption. While such a configuration optimizes fuel displacement by the wind turbine, more fuel might be required than if the load were met by operating a diesel with a lower incremental rate without the wind turbine. Net wind turbine output displaces diesel output kilowatt for kilowatt, but displaces fuel as a function of diesel incremental fuel rate.

Table 4-3 demonstrates the effect unit commitment can have on fuel displacement and efficient use of fuel. Table 4-3 values of fuel displacement, required fuel, and system efficiency were calculated using the incremental rates and idle fuel consumptions given in Table 4-2. Unit #8 was hypothetically operated under constant throttle. Unit #9 or unit #10 was hypothetically operated as the load frequency control diesel from which the wind turbine displaced fuel. Fuel displacement is that value calculated from the incremental fuel rate of the load frequency control diesel and the net wind turbine (WTG) output. Fuel required is the quantity of fuel flow required to meet the load as configured. System efficiency in kilowatt hours per pound of fuel is defined as:

$$\text{system efficiency} = \frac{\text{Total diesel output + Net Wind Turbine Output}}{\text{Fuel Consumed}} \qquad (4\text{-}7)$$

Configurations #5 and #10 of Table 4-3 demonstrate that displaced fuel can be greater with unit #10 on load frequency control as opposed to unit #9, but that the fuel required to meet the same load can be greater. Comparing configurations #3 and #10 shows that less fuel would be required to meet the same load with unit #9 on load frequency control without the wind turbine than with unit #10 on load frequency control with the wind turbine. Although any positive non-zero net wind turbine output displaces fuel, the system efficiency can be less with the wind turbine operational simply as a result of differing generation configurations.

TABLE 4-3
Fuel Displacement and Unit Dispatch

Configuration #	System Load kW	OUTPUT kW Unit #8	Unit #9	Unit #10	Net WTG	Fuel Disp. lbs./hr	Fuel Req'd lbs./hr	System Eff kWh/lb
1	250	150	100	Off	0	0	208	1.22
2	250	150	50	Off	50	25	183	1.37
3	250	100	150	Off	0	0	211	1.18
4	250	100	50	Off	100	49	162	1.54
5	250	100	125	Off	25	12	199	1.26
6	250	150	Off	100	0	0	253	.988
7	250	150	Off	50	50	29	224	1.12
8	250	100	Off	150	0	0	260	.962
9	250	100	Off	50	100	57	203	1.23
10	250	100	Off	125	25	14	246	1.02

Summary

A summary of fuel usage and displacement for the test period is given in Table 4.4. During the test period, unit #9 was used for load-frequency control, so that each kilowatt-hour generated by the wind turbine displaced 0.49 lbs. (0.067 gal.) of fuel (Table 4-2). Since the wind turbine auxiliaries consume electrical energy, the wind turbine auxiliary energy meter reading is subtracted from gross wind turbine output before total displaced fuel is calculated. Fuel displacement is equal to net wind turbine output multiplied by the incremental fuel rate.

During the test period, the MOD-OA wind turbine generated 10.7% of the system electrical energy requirement and reduced fuel usage by 6.7%. The different percentages are not inconsistent. Electrical output of a diesel comprises only a portion of fuel used by a generating diesel. Some fuel is always required to overcome mechanical losses; that quantity being the idle fuel consumption. Total fuel is equal to the fuel converted to electrical output plus the fuel required to overcome mechanical losses. Although the fuel displaced is proportional to the net wind turbine output, the total fuel used for generation is not linearly proportional to generation. Figure 4-4 demonstrates that for differing outputs, the kWh/lb of fuel is not a constant. Consequently, the net wind turbine output comprises a different percentage of burned fuel from that of electrical output.

Table 4.4

Fuel Displacement Results for Test Period

1)	diesel unit (unit #9) incremental fuel consumption	0.49 lbs. fuel/kWh
2)	gross MOD-OA wind turbine energy	56,900 kWh
3)	MOD-OA wind turbine auxiliary energy	4,470 kWh
4)	displaced fuel (line 2- line 3)x line 1	25,700 lbs. (3560 gal.)
5)	gross energy generated (diesel and wind turbine)	496,000 kWh
6)	total fuel burned	358,000 lbs. (49,800 gal.)

Conclusions

1) The rate of fuel displacement by the net output of the experimental MOD-OA wind turbine on Block Island is determined by the incremental fuel consumption rate of the diesel unit on load frequency control.

2) Diesel engine throttle activity, which results from wind gusts that change the wind turbine output, does not significantly influence fuel consumption.

3) The MOD-OA wind turbine on Block Island, Rhode Island displaced 25,700 lbs. of the diesel fuel during the test period; this reduced fuel consumption by 6.7% while generating a net 10.7% of the total electrical energy.

5. DYNAMIC INTERACTION

The objective of the dynamic interaction investigation was to quantify any increased disturbances to the Block Island power system resulting from connection of the MOD-OA. The combination of high wind energy penetration (60% maximum) on an electrically isolated utility offered the most likely potential for recording power system disturbances due to a wind turbine. The successful experimental operation of the Block Island MOD-OA installation resulted in generation of 588 MWh over a period of 32 months. The monitoring of the system for dynamic interaction took place with the instrumentation discussed in Section 3 during the period February into April, 1982. The potential dynamic interactions have been discussed in the literature and can be classified into four categories:

- Power and voltage transients due to the startup and shutdown sequence
- Power pulses as each blade passes through the tower wind shadow
- Power fluctuations due to wind gusts during fixed pitch control
- Power fluctuations due to wind gusts during variable pitch control

If these disturbances affect power at the customer level, the effect would be a fluctuation in voltage or system frequency. Some indication of the effects at the customer level can be interpolated from the recorded data at the point of generation. For the period of installation from mid 1979 to June 1982 of the Block Island MOD-OA and turbine, there were about 8500 hours of successful synchronous operation and approximately 4300 start-stop cycles during which voltage fluctuations were not noticeable to customers.

Infrequent periods of low winter load, gusting winds, and high blade pitch activity, can produce sizable disturbances in system frequency. This special case is discussed in detail and the frequency excursions are shown by a linear model investigation to be reduced by changes in the pitch control settings or by changing diesel governor settings.

5.1 Modes of MOD-OA Wind Turbine Operation

In this section are discussed the four modes of operation which may result in dynamic interaction with the Block Island system. These modes are:

- Startup and synchronization of the wind turbine generator
- Shutdown and cutout of the wind turbine generator
- Fixed pitch generation mode
- Variable pitch constant power generation mode

The above modes, in addition to other housekeeping functions, are automatically controlled by the microprocessor

5.1.1 Startup and Synchronization

Startup is normally initiated when the wind velocity measurements have exceeded 10 mi/hr for 58 of the last 64 seconds. The blade pitch is ramped from -90 degrees at controlled rates until 30 rpm is reached. The generator field is turned on and the rpm is cycled 3 times in 200 seconds about the 31.5 synchronous speed until the synchronizer closes the breakers. The synchronizer closes the breakers when the generator voltage and the system voltage remain within 20 degrees of each other for 0.2 seconds. The pitch control then ramps the power at 9.3 kW/s until the pitch angle reaches zero degrees (fixed pitch control) or until the power set point is reached (variable pitch control). A power and voltage transient will occur at the moment of generator synchronization. Additional detail can be found in ref. 14.

5.1.2 Cutout and Shutdown

In this category of operation, three types of shutdown can occur. The first, referred to as normal shutdown, occurs as the result of wind speed being either too high (> 40 m/hr) or too low (< 8 m/hr). When such wind speed conditions are sensed, the automatic microprocessor control causes blade pitch angle to be decreased at the rate of .8 degrees/second until the WTG power reaches zero. At this time, the break trips, electrically disconnecting the WTG from the utility. The blade pitch then continues to its fully feathered position of -90.

For the second type of shutdown, emergency, the emergency feather valves are opened to change the blade pitch at a rate of 4^{o}/seconds and also the hydraulic pump is turned off in case the emergency solenoid fails to respond. This type of shutdown occurs when any one of several key operational factors exceeds its safe operating limit.

A third type of shutdown operation, referred to as critical shutdown is so named because it is initiated when the rotor exceeds the so-called critical speed. At this time, the following major events occur simultaneously: (1) 4^{o}/second blade pitch ramp down begins, (2) rotor brakes applied, (3) tie breaker opens. Because this is not a controlled shutdown in the sense that the normal and emergency shutdowns are, the step change in WTG power can cause a severe transient in the system frequency. The larger this switched power, the larger the system frequency disturbance. It is also possible for the tie breaker to open -- interrupting power -- in the absence of critical shutdown conditions. Causes for such a non-zero WTG power breaker trip include: (1) overcurrent (should occur only for a fault), (2) current unbalance (neutral current flow), (3) reverse power, (4) spontaneous relay triggering (induced by electrical noise). Although these non-zero power interruption events were infrequent, the resulting frequency transients were the largest observed. It is therefore clearly desirable to minimize any falsely originated breaker trips and/or prevent any rapid changes in WTG power.

5.1.3 Fixed Pitch Operation

The power setpoint on the Block Island MOD-OA is manually adjustable from zero to 150 kW. The purpose of lower than maximum settings is to prevent the controlling diesel from dropping to less than 50% rated output during low loads which would result in the oiling problem discussed in Section 4 (such operation is not intended to normally occur and is reserved only as a special contingency). Fixed pitch operation occurs when the wind supplies less power than the power set point. The blades are fixed at zero degrees optimizing wind power transfer but resulting power output which varies with the wind speed squared. The variations in wind turbine power output -- in addition to normal system load changes -- cause system frequency fluctuations which result in control action by the diesel speed governor.

5.1.4 Variable Pitch Operation

When wind power rises above the power setpoint, the pitch control system begins operation to maintain an average power equal to the setpoint. The pitch control system consists of a power measurement transducer, a manual power setpoint control, a proportional-plus-integral feedback function, and a hydraulic actuator which pitches the blades. The resulting pitch action reduces power fluctuations due to wind variations; however, data from Block Island has shown that the system frequency varies substantially more with variable pitch and low power setpoints than under fixed pitch operation. An explanation of the larger than expected frequency variations and suggested solutions are presented in the following section.

5.2 Analysis of Dynamic Interaction

During the three month study period, the strip chart record revealed dynamic interactions from each of the four expected categories. Startup and shutdown transients were found to be of such short duration that their character could only be observed on strip charts recorded at several times the normal speed (6 mm per minute) and on data tapes of the voltage regulation tests which were sampled at 10 samples per second.

The effect of the blades passing through the wind shadow of the tower resulted in a cyclic power variation at twice the rotor speed of 31.5 rpm. The resulting 6.6 rad/s power oscillation had a wide range of amplitudes, depending on wind condition and pitch cycle. Fixed pitch operation resulted in power fluctuations requiring governor action to compensate for gusts of wind. Variable pitch operation resulted in increased governor action due to an often sustained power system oscillation of 0.9 rad/s frequency corresponding closely to the natural frequency of the system without the wind turbine.

5.2.1 Characteristic Diesel Dynamics Without The MOD-OA

The Block Island power system has a response to load changes which causes the system frequency to swing for one or two cycles at a rate of 0.9 rad/s to 1 rad/s (6 to 7 sec period). Figure 5-1 shows the response of the system with the wind turbine disconnected and normal load fluctuations present. A natural oscillation of 0.97 rad/sec can be seen in the system frequency. A typical oscillation will swing 0.13 Hz peak-to-peak in frequency and 9 kW peak-to-peak in load. Figure 5-2 shows a one minute interval during which an approximate step change in system load of 11 kW occurred. The system frequency begins an initial rate of decrease of 0.15 Hz/s. The unit #9 governor responds to the frequency drop by increasing the throttle 2^0 (27 kW mechanical power) and then dropping slightly as the frequency overshoots and settles down to 60 Hz. This response is underdamped and representative of a normal diesel load response with an isochronous governor setting.

A 40-minute interval of strip chart recording is reproduced in Appendix Figure B-12 showing the typical system fluctuation without the MOD-OA connected. The largest frequency fluctuations shown are 0.4 Hz peak-to-peak (60 Hz $\pm$ 0.2 Hz).

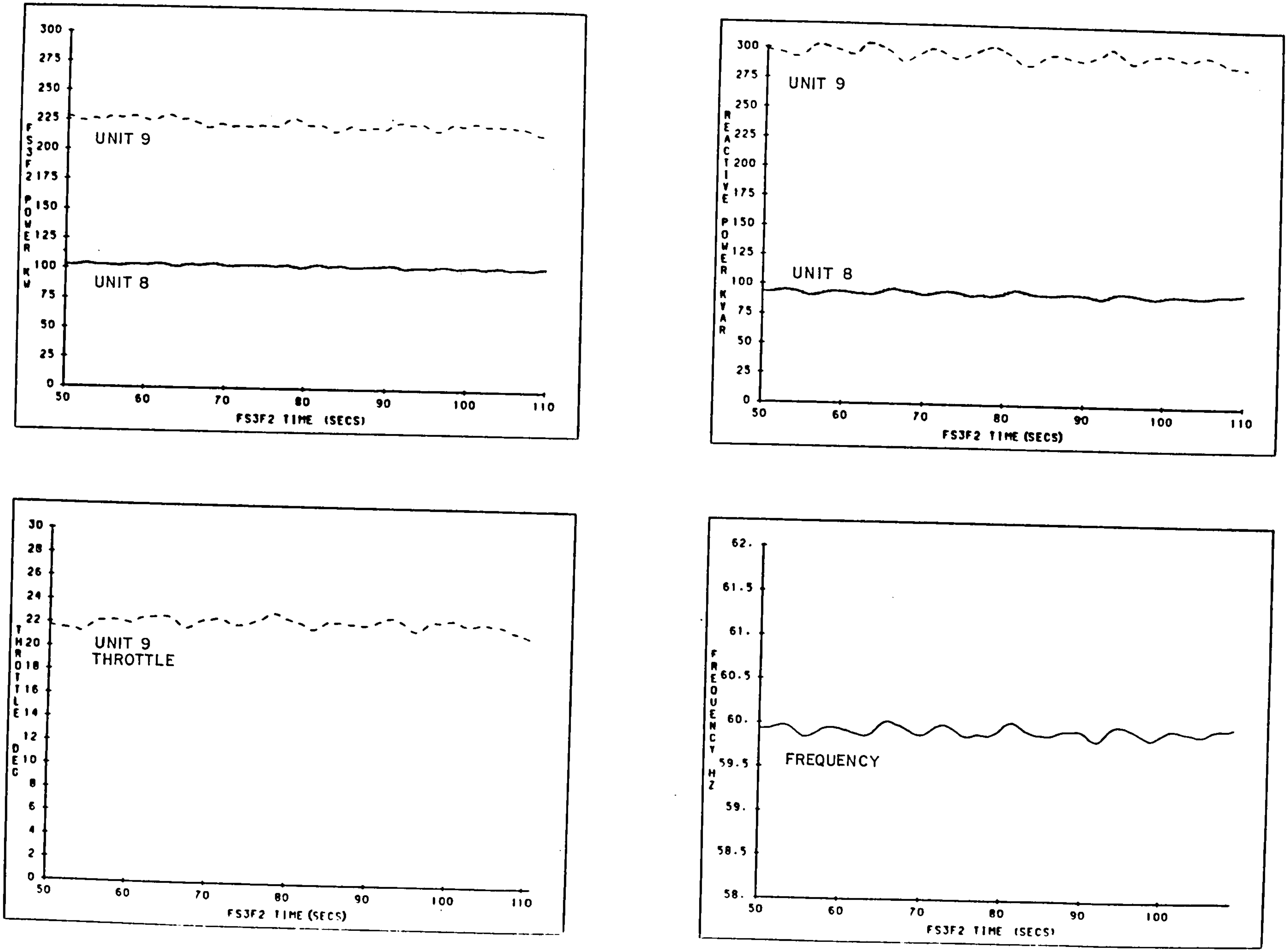


Figure 5-1. Diesel System Response to Load Fluctuations

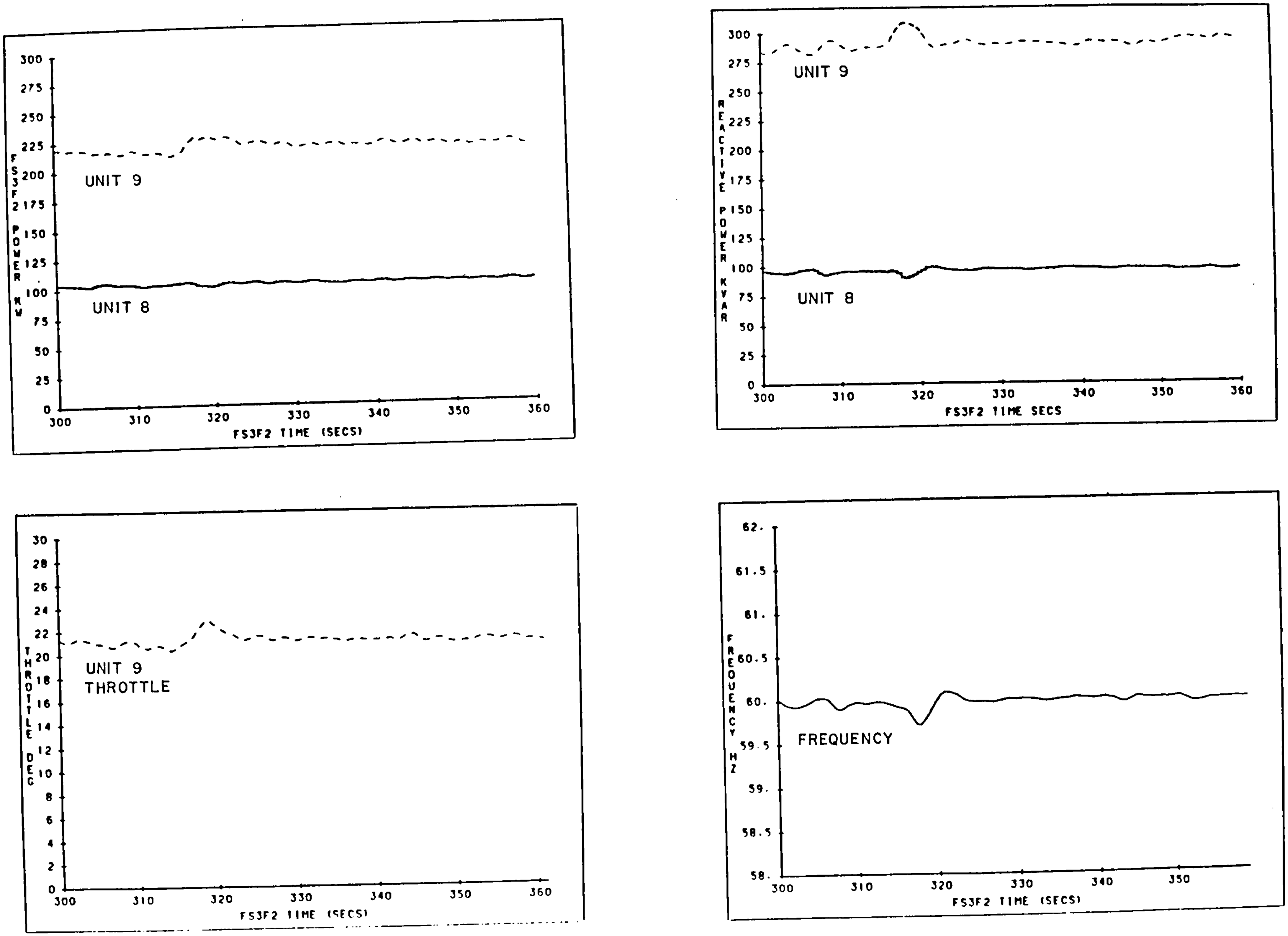


Figure 5-2. Diesel System Response to Load Change

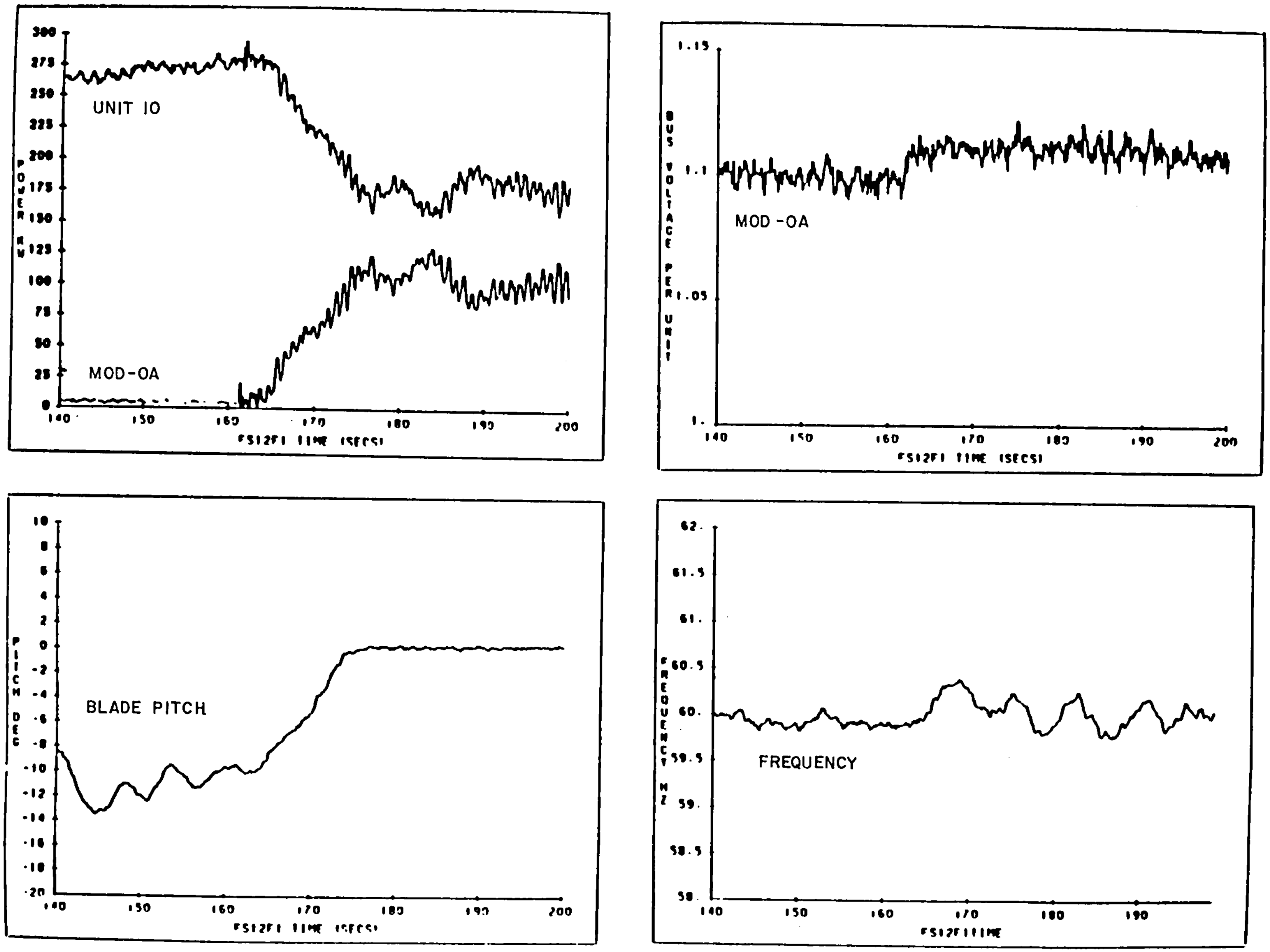


Figure 5-3. MOD-OA Startup and Synchronization for Low Wind Condition

5.2.2 Dynamic Behavior During Startup

The synchronizing procedure detailed in section 5.1.1 results in varying degrees of disturbance even though microprocessor controlled. The following startup/synchronizing events cover the range of operation.

The typical short transient due to generator synchronization can be seen in the low wind startup operation shown in Figure 5-3. The wind turbine power has a damped oscillation of .8 rad/s and an initial peak of 17 kW. The magnitude of the power transient decreases below the measurement capability within an interval of 0.8 second. The diesel power has an identical but reversed power transient. The frequency and governor throttle do not change for such a short term effect. The average voltage at the MOD-OA bus rises 1.4% due to the generation of reactive power. This voltage change compares to normal fluctuations of 1% occurring during each second.

Figure 5-4 is an example of startup in a moderate wind condition (≈ 16 m/hr). The synchronizing disturbance in WTG power is nearly invisible -- only the small reactive power step defines the point where the tie breaker closes in. (As the power is ramped up reaching 130 kW, suddenly the tie breaker opens suggesting that a critical shutdown has occurred inasmuch as the microprocessor begins ramping down the blade pitch angle at the rate of 4^{o}/s.)

A high wind startup appears in Figure 5-5. At the point of synchronizing, the wind speed is about 35 m/hr and a moderate transient disturbance is observed. Immediately following synchronization, the pitch angle is decreasing and a short interval of motoring results. Recovery into the generating mode is rapid enough to avoid shutdown, and the power ramps up to the 200 kW level. A gusty interval then ensues which in some way causes an emergency shutdown (power is rapidly ramped to zero before the breaker opens).

Figure 5-6 reveals the nature of the system frequency (the mode produced by the alternator and blade hub inertia and air gap torque spring

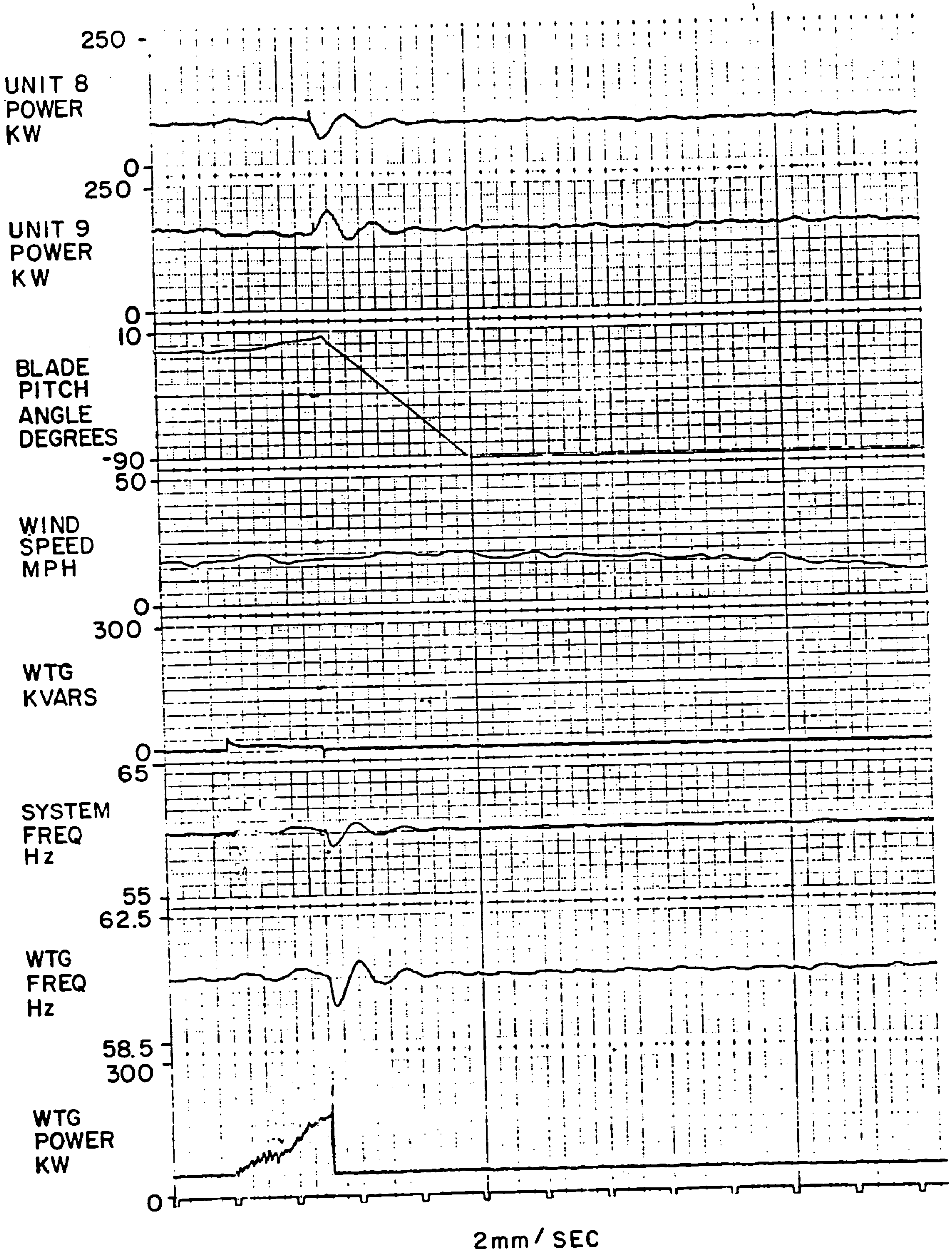


Figure 5-4. MOD-OA Startup and Synchronization in Moderate Wind Condition

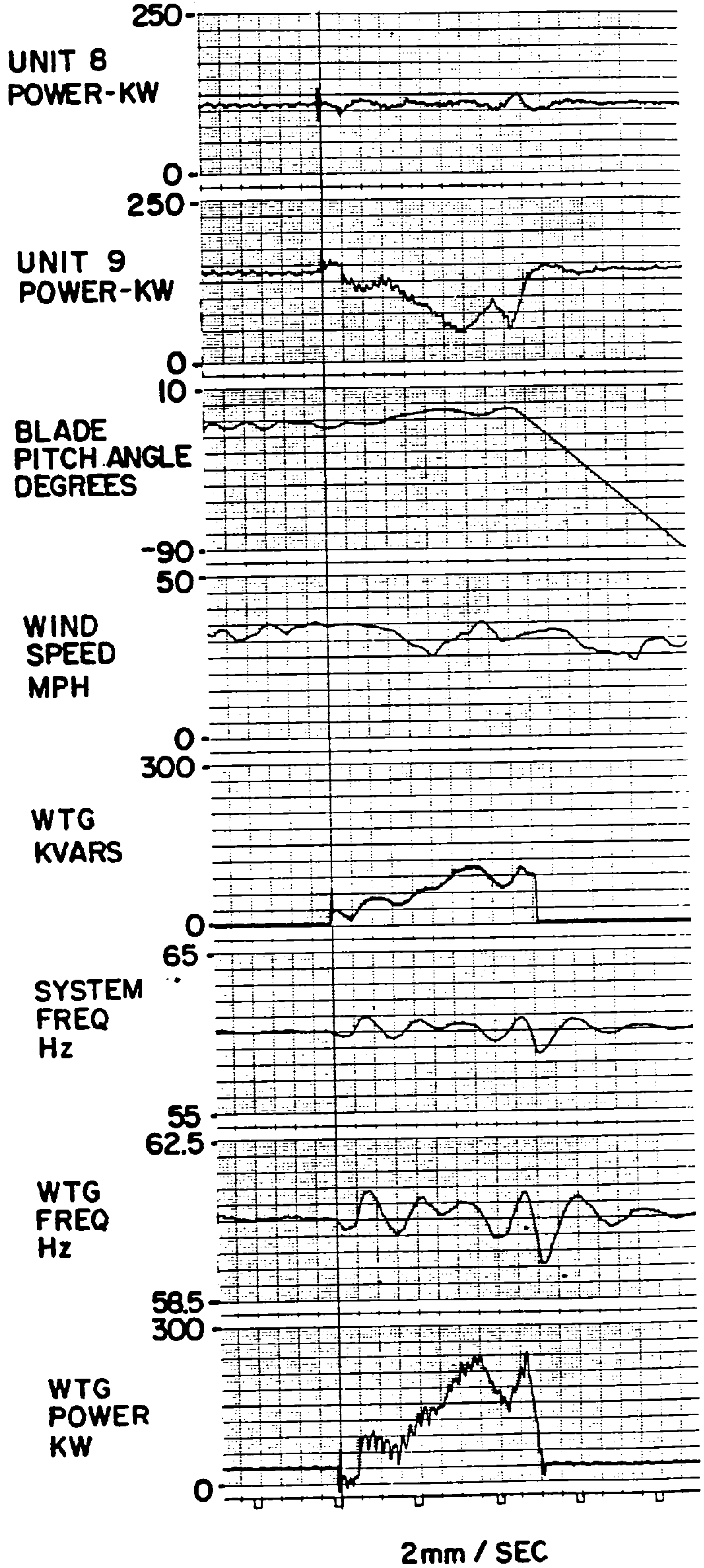


Figure 5-5. MOD-0A Startup and Synchronization for High Wind Condition

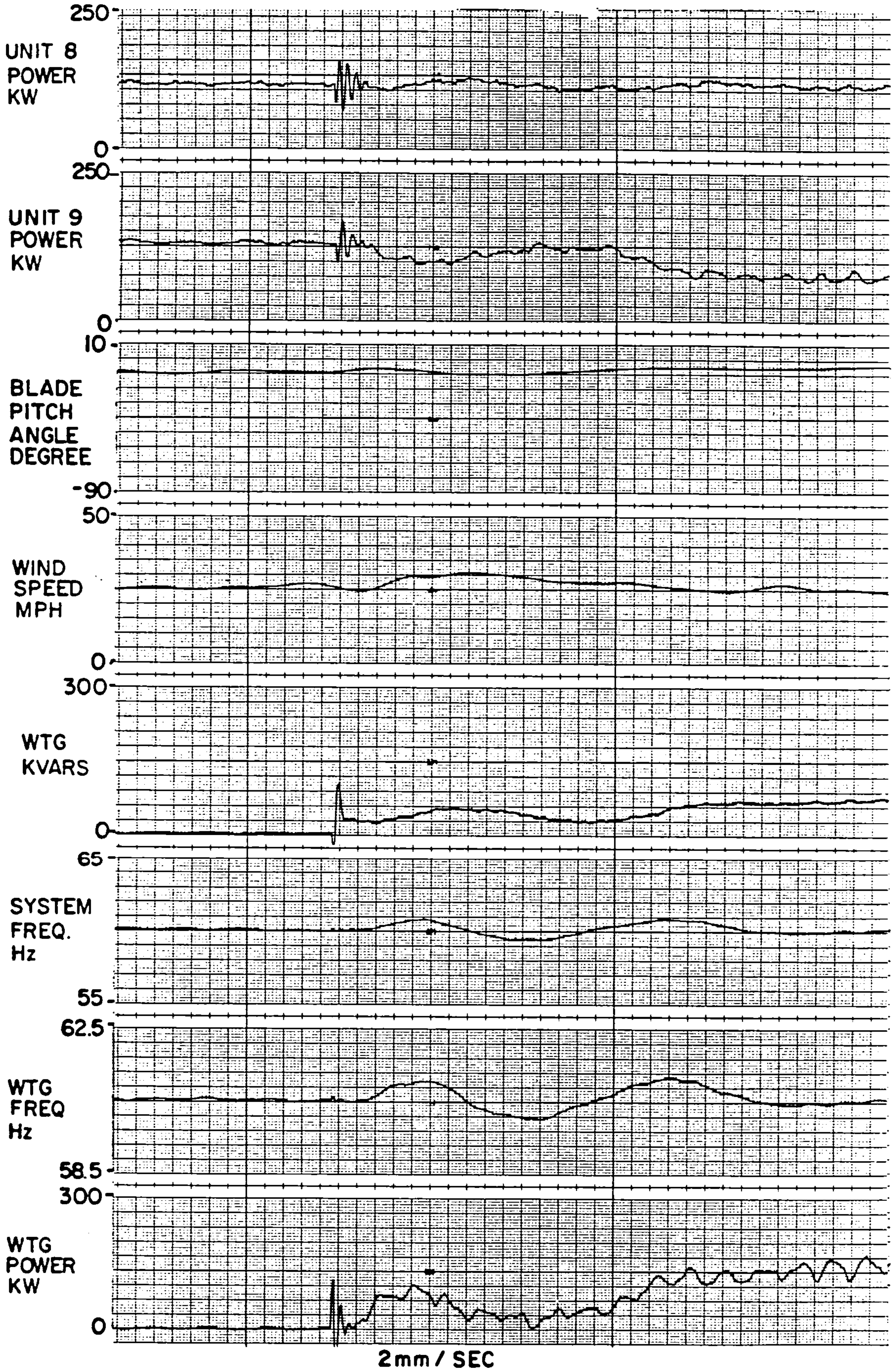


Figure 5-6. MOD-OA Synchronization Transient

constant) when synchronization of the MOD-OA with the utility occurs. A value of about 4.5 Hz is measured. The wind turbine power transient is seen to be relatively well damped -- about 50% per cycle. The plots of power for diesels #8 and #9 show the 4.5 Hz damping to appear considerably lower. A possible explanation of this phenomenon is that modal frequencies close to 4.5 Hz are present in the dynamics of the diesels. This seems likely when viewing the #8 diesel generator power transient since there is an evident buildup of the 4.5 Hz natural frequency component of the power transient before it decays to zero.

5.2.3 Dynamic Behavior During Shutdown and Cutout

While the objective of the previous section was to examine startup/synchronization, some shutdown operations were also discussed. The latter is now the main point for discussion in this section, where cases covering normal, emergency and critical shutdown modes are examined.

A typical low wind speed normal shutdown operation appears in Figure 5-7. The typical shutdown case is shown in Figure 5-7. No transient is observed in power or voltage during the generator disconnection.

An emergency shutdown case appears in Figure 5-8. Here synchronization occurs at a wind speed of about 17 m/hr. Wind speed subsequently decreases and the blade pitch angle responds to increase power towards the 150 kW setpoint. Then a wind gust reaching 37 m/hr results in the microprocessor signaling for an emergency shutdown as verified by the presence of the $-4^{o}/s$ ramp of the blade pitch angle. Such a windspeed alone (37 m/hr) would usually result in a normal ($-1^{o}/s$) shutdown. Some other cause, e.g. excess vibration, is probably the reason for the emergency mode occurring. Although the breaker does not trip until the WTG power passes thru zero, the frequency transient that results is same 2 Hz peak-to-peak. This would suggest that changes in WTG power exceeding about 35 kW/s will begin to appear to the system as power step changes.

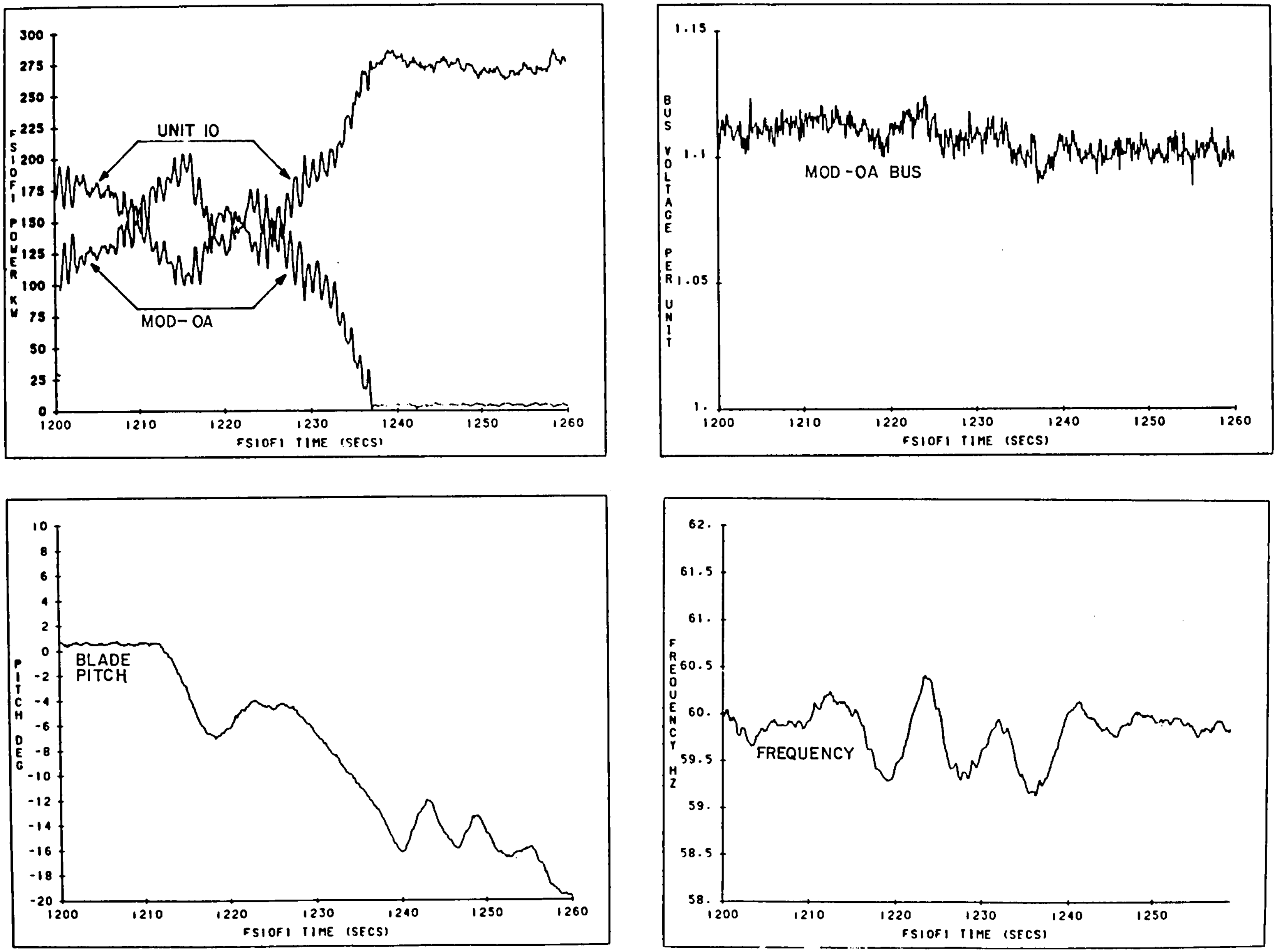


Figure 5-7. MOD-OA Shutdown and Cutout. Tower Shadow Effect (6.6 rad/s) and Natural Frequency (0.7 rad/s) are Present.

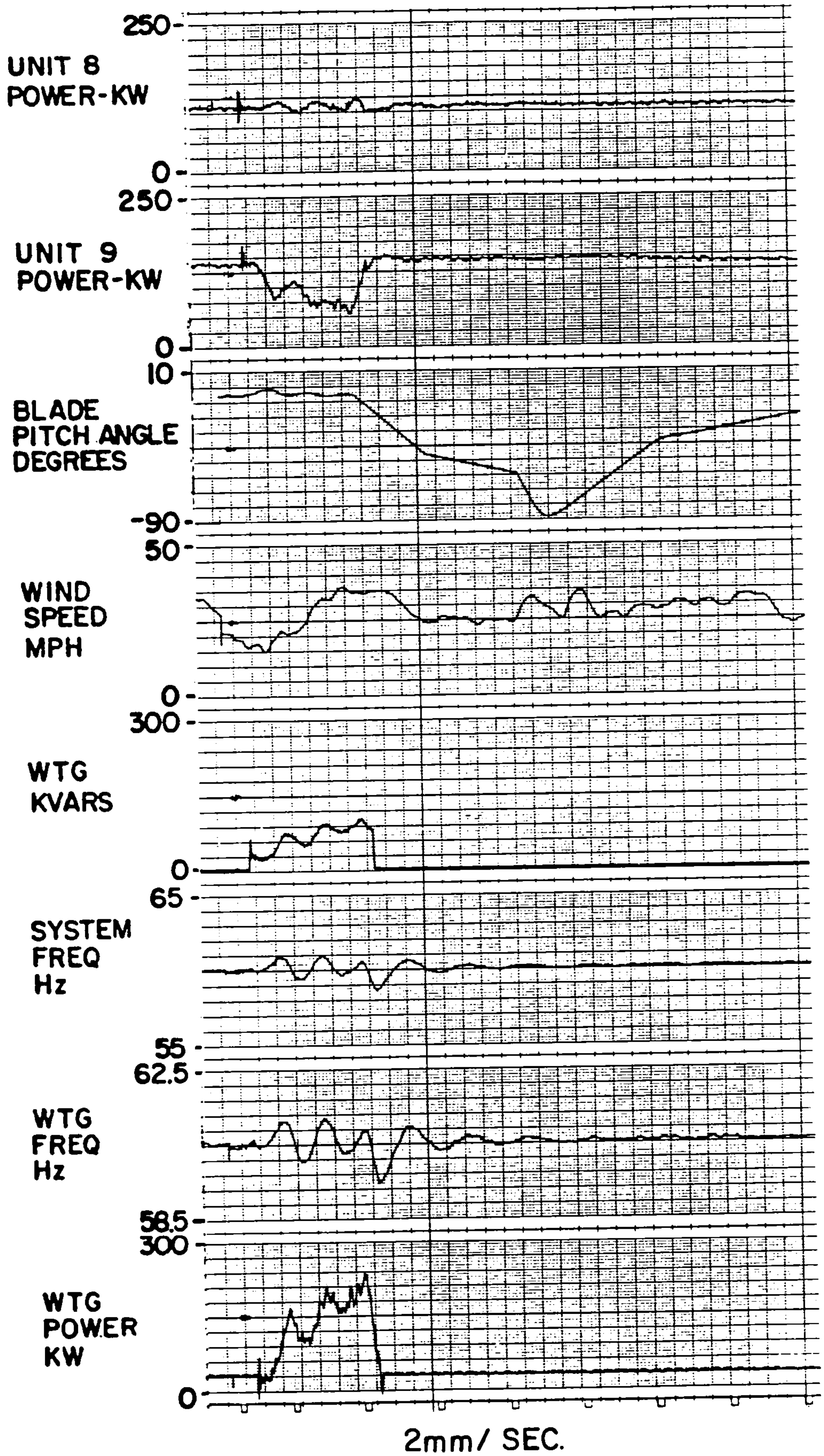


Figure 5-8. MOD-OA Emergency Shutdown-High Wind

Figure 5-9 shows a normal shutdown due to high wind conditions. In this instance, the -1^{o}/s blade pitch change results in a much more gradual WTG power ramp down, so that the frequency transient is no more than 0.6 Hz peak-to-peak.

Figure 5-10 shows an event resulting in probably the most severe frequency transient of the 3 month data collection period. As seen in channel 4, a wind gust of about 8 miles per hour per second occurs, resulting in a peak WTG power of about 250 kW. This gust probably initiates critical shutdown due to rotor overspeed and the breaker is tripped instantaneously.

Because this appears to the system as a large step load increase, the power out of both diesel units #8 and #10 indicate a step increase, with the power of #8 returning to the pre-event power level within several seconds while governor action (to keep the average system frequency constant) causes #10 to increase power by the amount the WTG had been supplying.

Since the breaker opened some 1.5 seconds before the blade pitch angle changed, the potential for blade overspeed existed. However, the rapid change (-4^{o}/s) of the pitch angle and presumed rotor brake application would avoid this problem.

As seen in channels 6 and 7, the peak to peak frequency excursions reach 3 Hz. In addition to the severity of this frequency excursions, the inherent diesel governor damping on this particular date is clearly revealed -- yielding a damping factor (ζ) of about .12. This value is considerably less than that exhibited by Figures 5-9 and 5-8 and points out the degree of dynamic variability of the BIPCO system alone.

5.2.4 Wind Shadow Dynamic Interaction

As each blade passes through the wind shadow of the tower (63 times per minute), the resulting downward power pulse is damped by a combination of blade inertia and the fluid coupling forming a cyclic power oscilla-

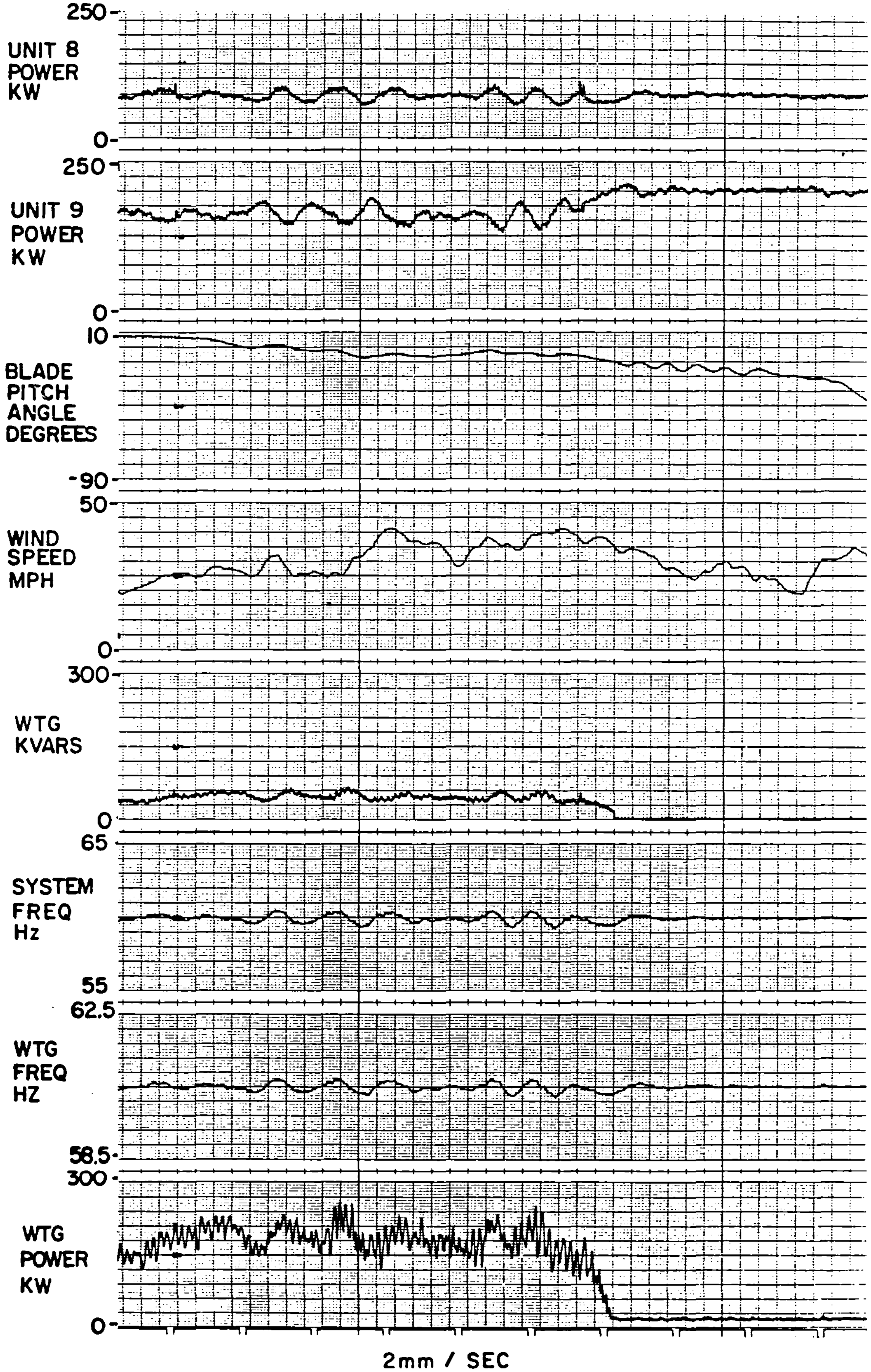


Figure 5-9. MOD-0A Normal Shutdown-High Wind

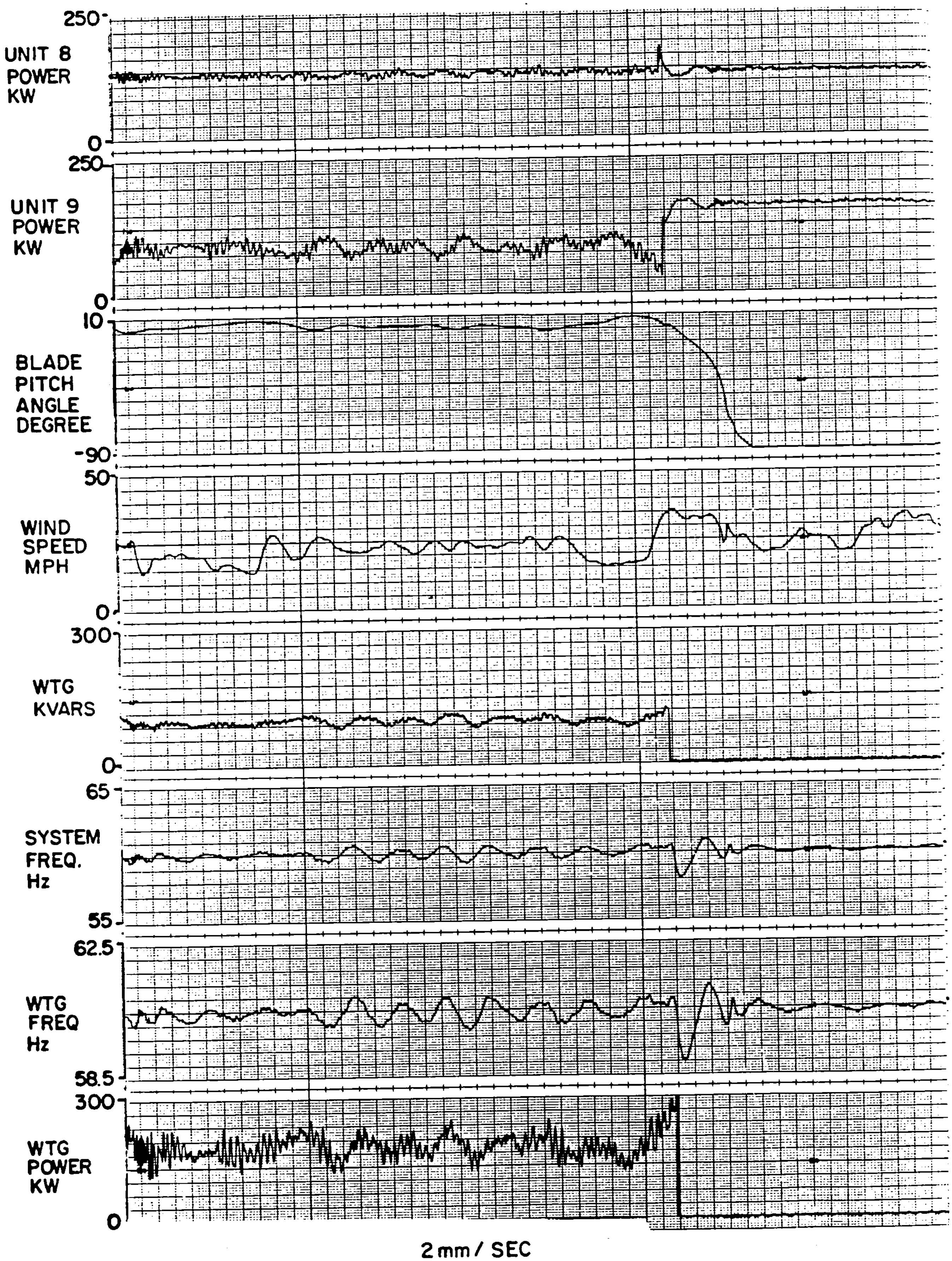


Figure 5-10. MOD-0A Abnormal Shutdown

tion of frequency 6.6 rad/s. Figure 5-3 shows an example of this effect with amplitudes of 10 to 32 kW variation apparent in the wind turbine power output. The diesel generator output follows a mirror image of the MOD-OA power because the power requirement of the load remains relatively constant throughout these intervals. (Because units #9/#10 are larger than unit #8, the tower shadow power variation seen on units #9/#10 will be similarly larger. For constant load demand, the tower frequency variational power should equal the sum of that units #8 and #9/#10.) The voltage and frequency are not observed to vary measurably with this cyclic variation in power. The diesel governor has shown a small tendency to respond to this variation though it appears the amplitude is usually within the deadband of the governor response.

The appendix Figure B-11 shows a 20-second interval of strip chart data recorded 50 times the normal speed of 6 mm per minute. The tower-shadow effect is clearly evident as an oscillation with period of 0.95 second. Similar oscillations are apparent in Figures B-4 to B-9. The typical amplitude for the power variation is 30 kW, though amplitudes as great as 60 kW have been observed for a few seconds. These largest amplitudes caused a 0.13 Hz amplitude oscillation in the system frequency and a one degree (13.5 kW) oscillation in the unit #9 throttle position. These disturbances are within the range of normal load fluctuations.

5.2.5 Dynamics Interaction during Fixed Pitch Mode

The connection of the wind turbine results in increased disturbance to the system. Appendix figures B-13 and B-14 show the disturbances on the system increasing due to the connection of the wind turbine. The MOD-OA under fixed pitch control causes frequency and power variations that are of the same magnitude as the largest load fluctuations though occurring more frequently. The response of the system during wind gusts is representative of the worst case of system disturbance during fixed pitch control. A one minute example of a wind gust and the response of the system is shown in Figure 5-11 with corresponding nacelle wind speed in Appendix D, Figure D5-11. The pitch control is shown just reaching the

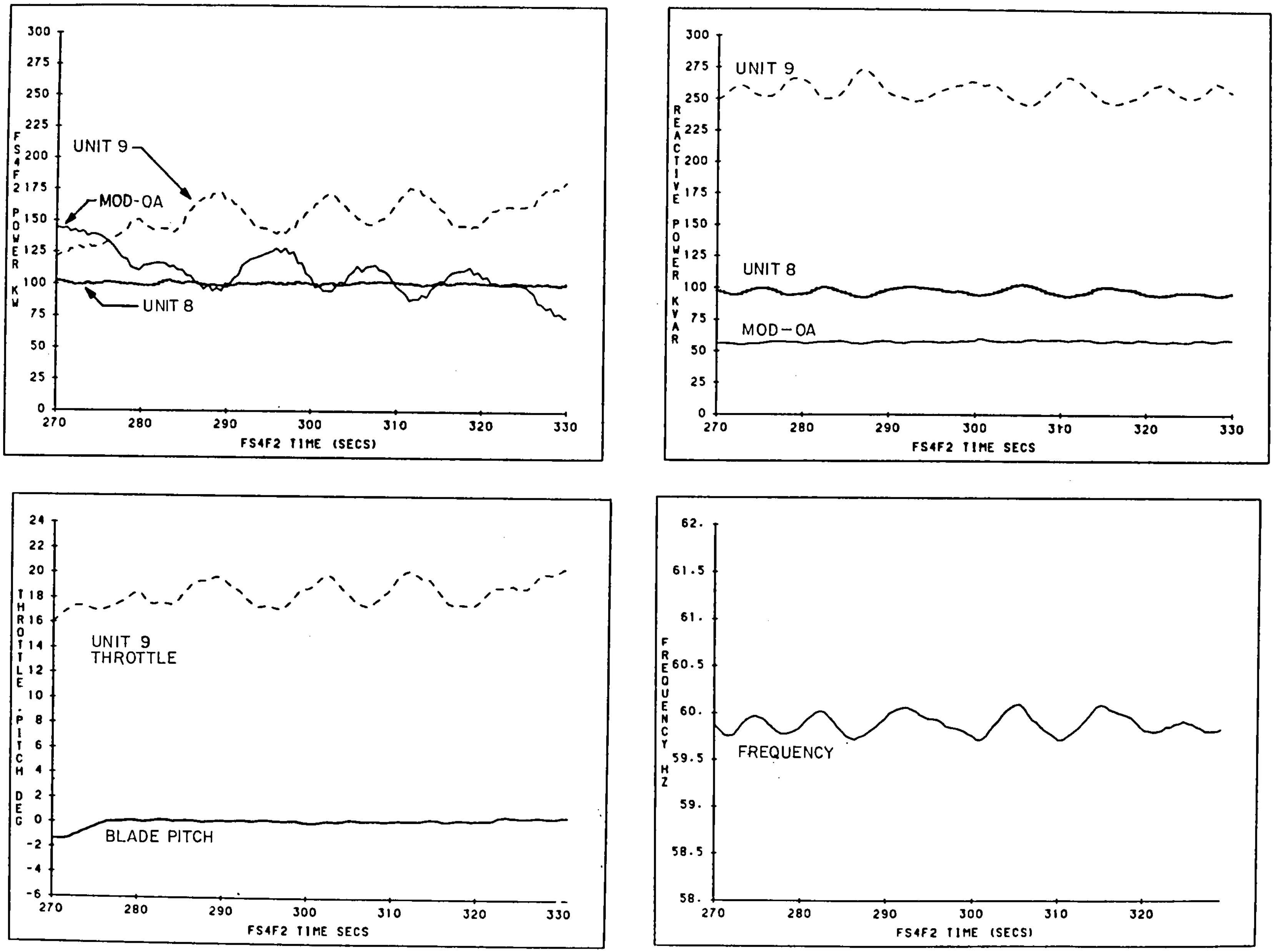


Figure 5-11. System Response During Fixed Pitch Operation (150 kW Power Setpoint) Tower Shadow Effect Filtered Out for Clarity.

fixed pitch point as the wind begins a downward and then upward gust. An oscillation is excited in the system with a frequency of 0.63 to 0.86 rad/s. The system frequency swings of 0.38 Hz peak-to-peak during wind gusts correspond to turbine power variations of 26 kW peak-to-peak. The diesel unit #9 output supplies the difference in electric power between the system load and MOD-OA generation. The inequality between the diesel mechanical power (controlled by the governor throttle) and the electric output requirement results in speed changes which are observed as system frequency changes. The governor responds to a change in frequency by moving the throttle angle to bring the frequency to 60 Hz. Under fixed pitch control the diesel governor successfully damps the effect of a wind gust such as in Figure 5-11 after two or three cycles (under 30 seconds)

5.2.6 Dynamic Interaction During Pitch Control Mode

The pitch control mode is engaged when the wind turbine power output exceeds the setpoint value (normally 150 kW). The blade pitch angle is then decreased from the fixed pitch angle (zero degrees) and continuously controlled for constant power output. The result of the pitch control engaging at the 150 kW setpoint on the Block Island system can be seen in Figure B-2. The pitch control action results in the average power output being equal to the power setpoint; however, a 0.9 rad/s power oscillation has been produced where amplitudes exceed 60 kW peak-to-peak several times in this example. The magnitude of the system frequency oscillation reaches 1 Hz peak-to-peak. This oscillation also occurs in the parameters of power, system frequency, current, and voltage with amplitudes much larger than normally found under fixed pitch control. Large amplitude oscillations were observed when the power setpoint was set at 25 kW to 100 kW and the wind was gusting during variable pitch control operation.

Examples of this are shown in Figures B6 through B8 where the power setpoint is equal to 50 kW. The magnitude of the system frequency oscillation approaches 2 Hz peak-to-peak, while power oscillations approach 100 kW peak-to-peak.

Figures 5-12 and 5-13 show the system with the power setpoint on the MOD-0A set at 150 kW and the pitch control becoming active as the power output exceeds 150 kW. The power output begins decreasing as the pitch angle is decreased. In both figures, an oscillation of about 0.8 rad/s frequency begins just as the power output is brought down to the power reference point. In Figure 5-13, the system frequency swings 0.7 Hz peak-to-peak. The power output swings 40 kW peak-to-peak, and the pitch angle swings 1.7^0 peak-to-peak (roughly 34 kW peak-to-peak wind power).

Figures 5-14 and 5-15 show system response during continuous (uninterrupted) pitch control. The dominant undamped oscillation is evident at all times and is very similar in form despite the difference in nacelle wind speed seen in figures D5-14 and D5-15.

The internals shown in Figures 5-16 and 5-17 indicate that the amplitude of the low frequency (.9 rad/s) oscillation is nearly double that appearing in Figure 5-14 and 5-15. There are two factors which could contribute to this difference: (1) the power setpoint in Figures 5-16 and 5-17 is at 50 kW rather than the 150 kW setpoint in Figures 5-14 and 5-15, (2) the wind speed profiles (Figures D5-16 and D5-17) which are observed to be considerably more gusty in nature.

It should be noted that 50 kW power setpoint would not be representative of normal operation because of the underutilization of WTG capability. However, it is necessary to determine whether low power setpoints inherently lead to higher oscillation amplitudes and conceivably, WTG damage. A further evaluation of the available data recordings has enabled this question to be more or less resolved.

Figure 5-18 shows an interval during which the power setpoint is switched from 150 kW to 50 kW. Prior to the transition point, the blade pitch controller can be seen to be going into and out of variable pitch control. Here the peak-to-peak power frequency variations are less than .5 Hz. As the transition is made from the 150 kW to the 50 kW power setpoint, the variations reach 1 Hz. This difference is attributed to periods of fixed pitch operation occurring at the 150 kW

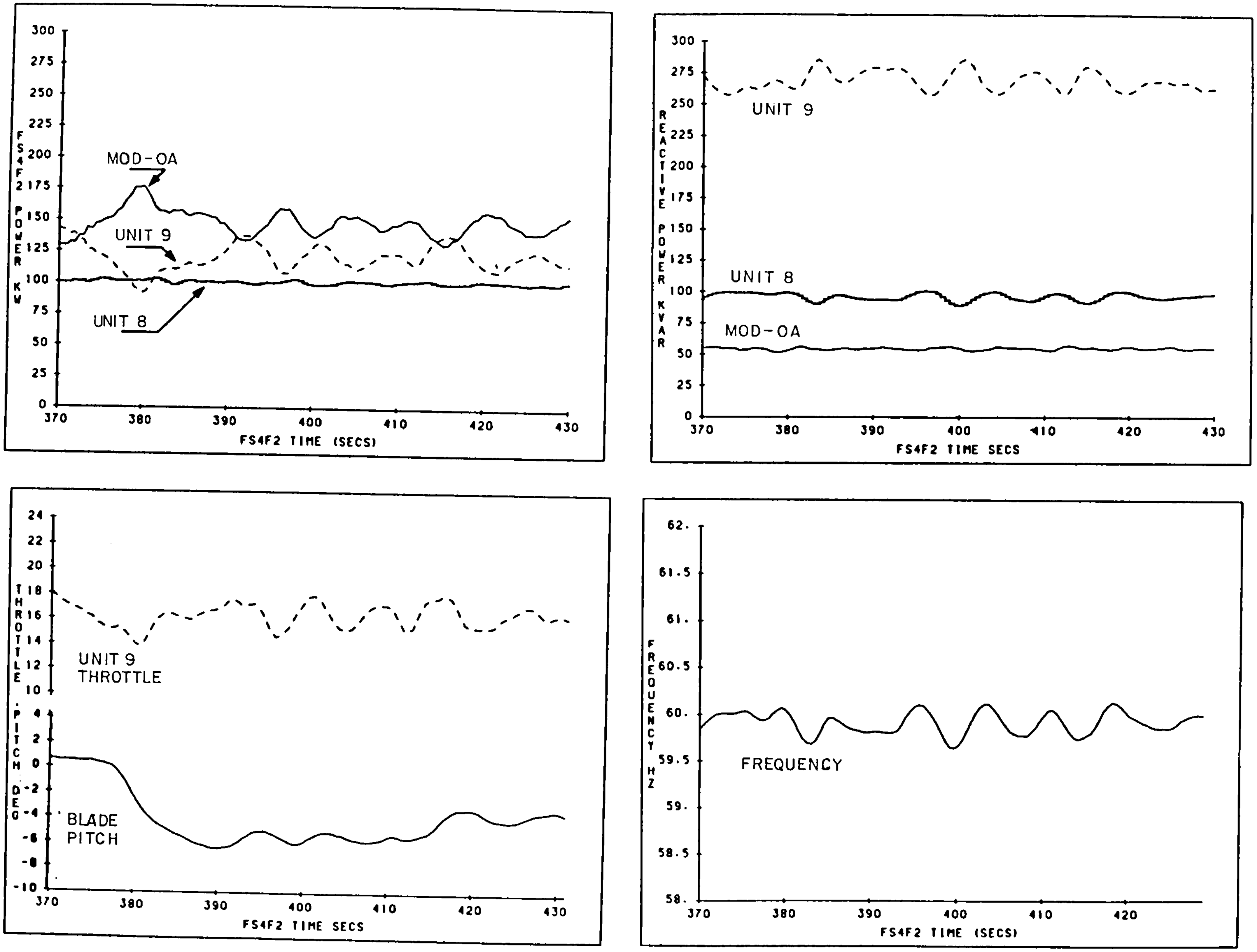


Figure 5-12. System Reponse at Onset of Pitch Control (150 kW Power Setpoint) Tower Shadow Effect Filtered Out for Clarity.

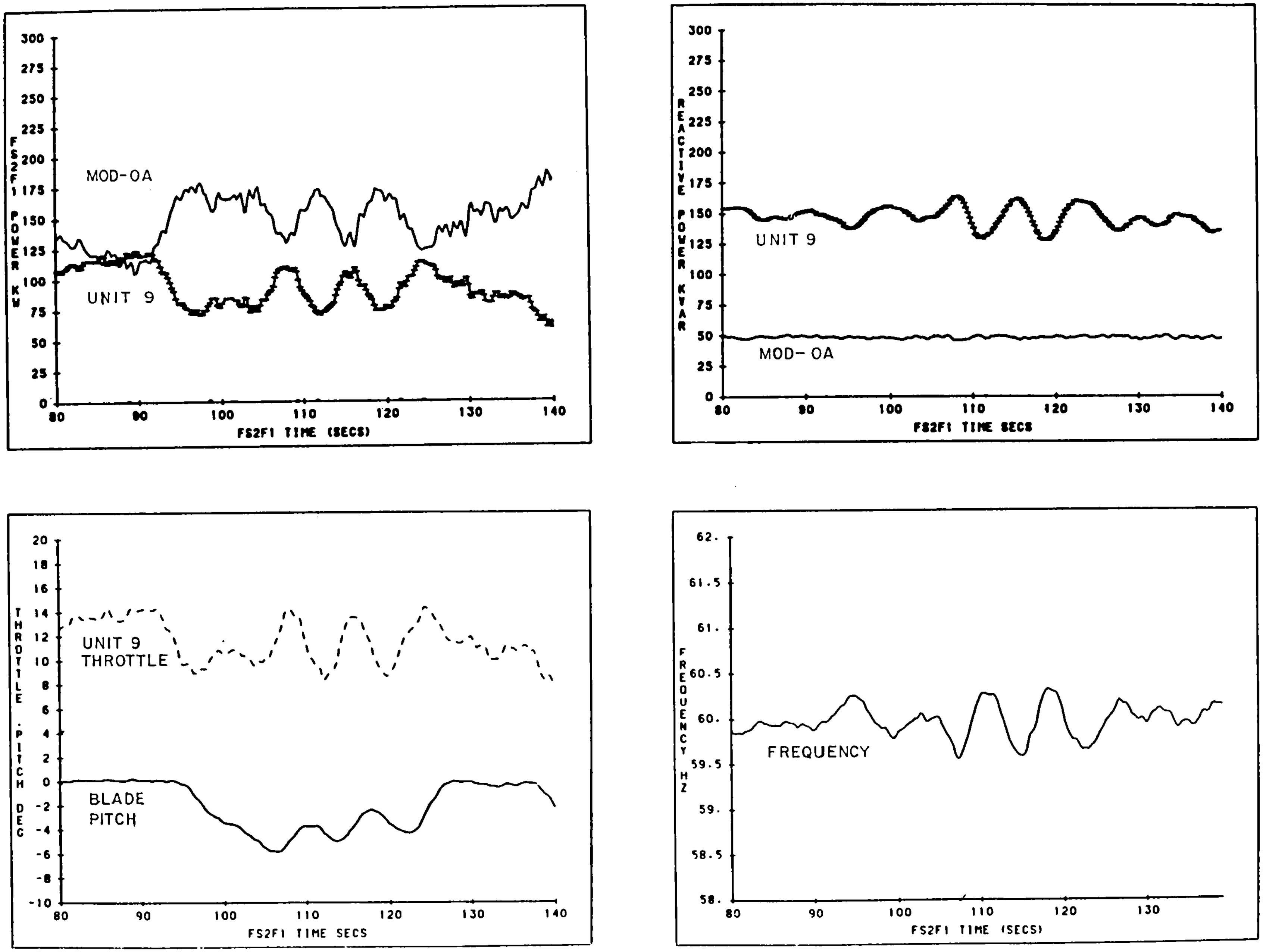


Figure 5-13. System Response During Intermittent Pitch Control (150 kW Setpoint) Tower Shadow Effect Filtered Out for Clarity.

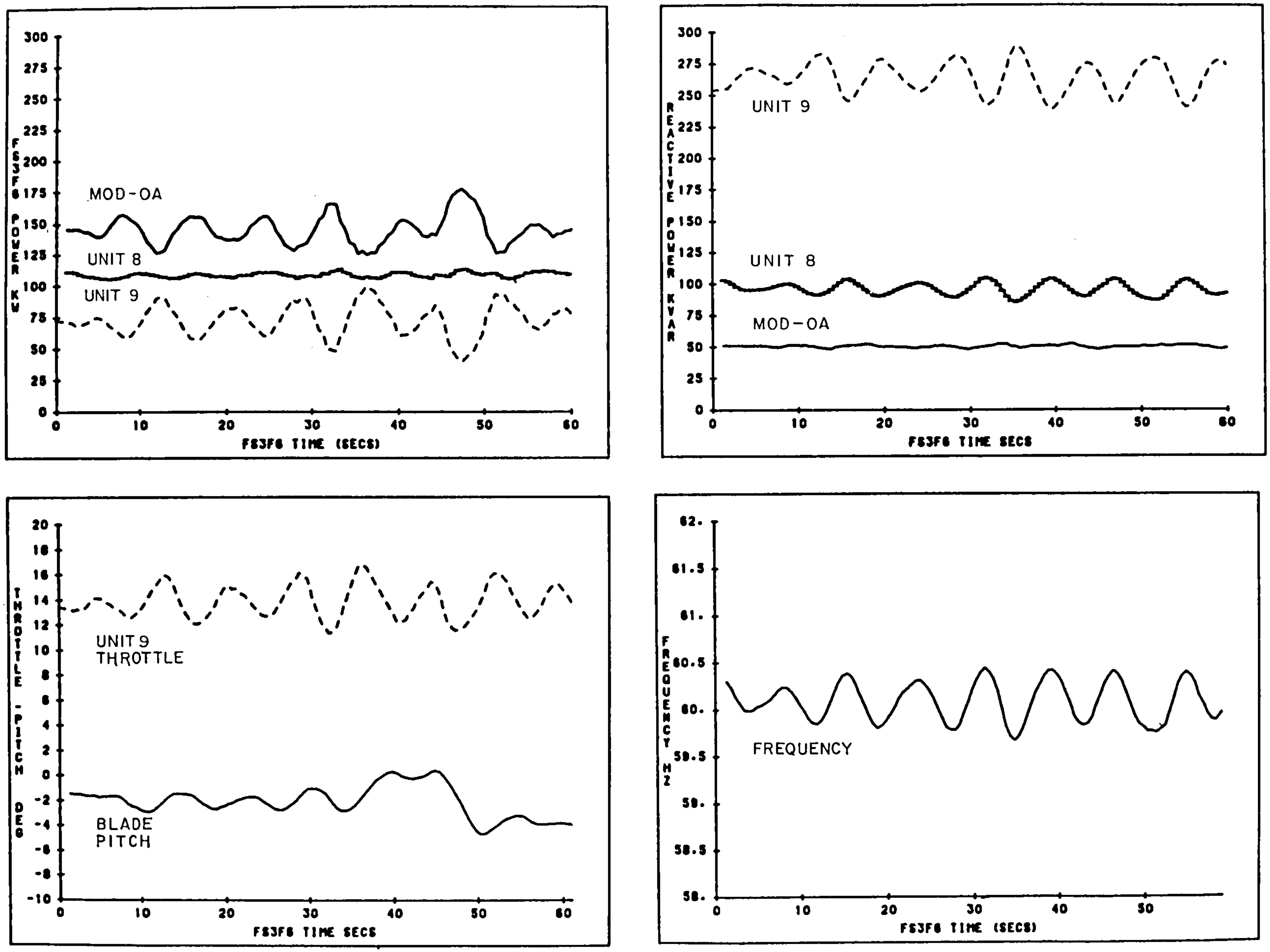


Figure 5-14. System Response During Pitch Control (150 kW Power Setpoint) Tower Shadow Effect Filtered Out for Clarity.

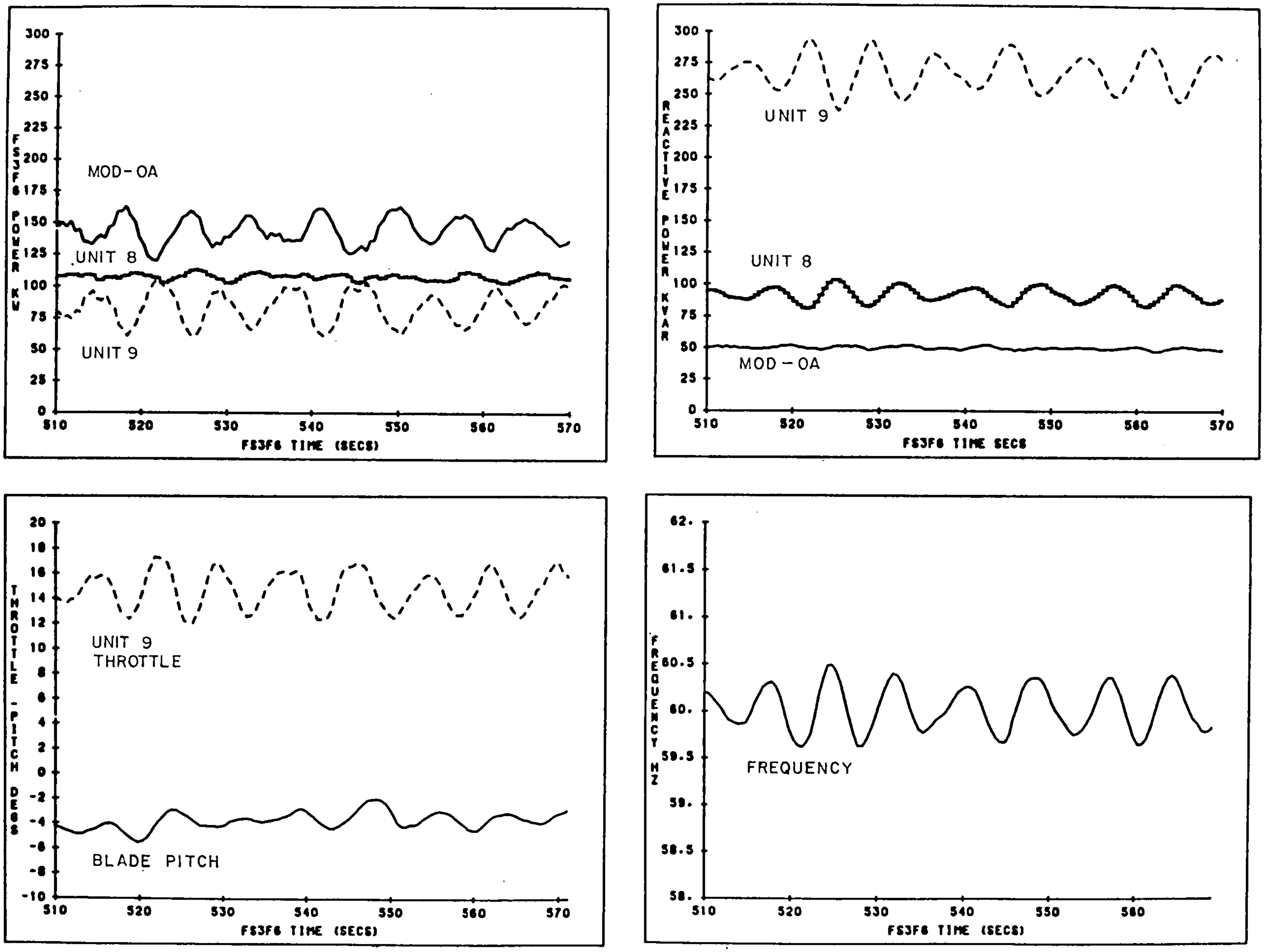


Figure 5-15. System Response During Pitch Control (150 kW Power Setpoint) Tower Shadow Effect Filtered Out for Clarity.

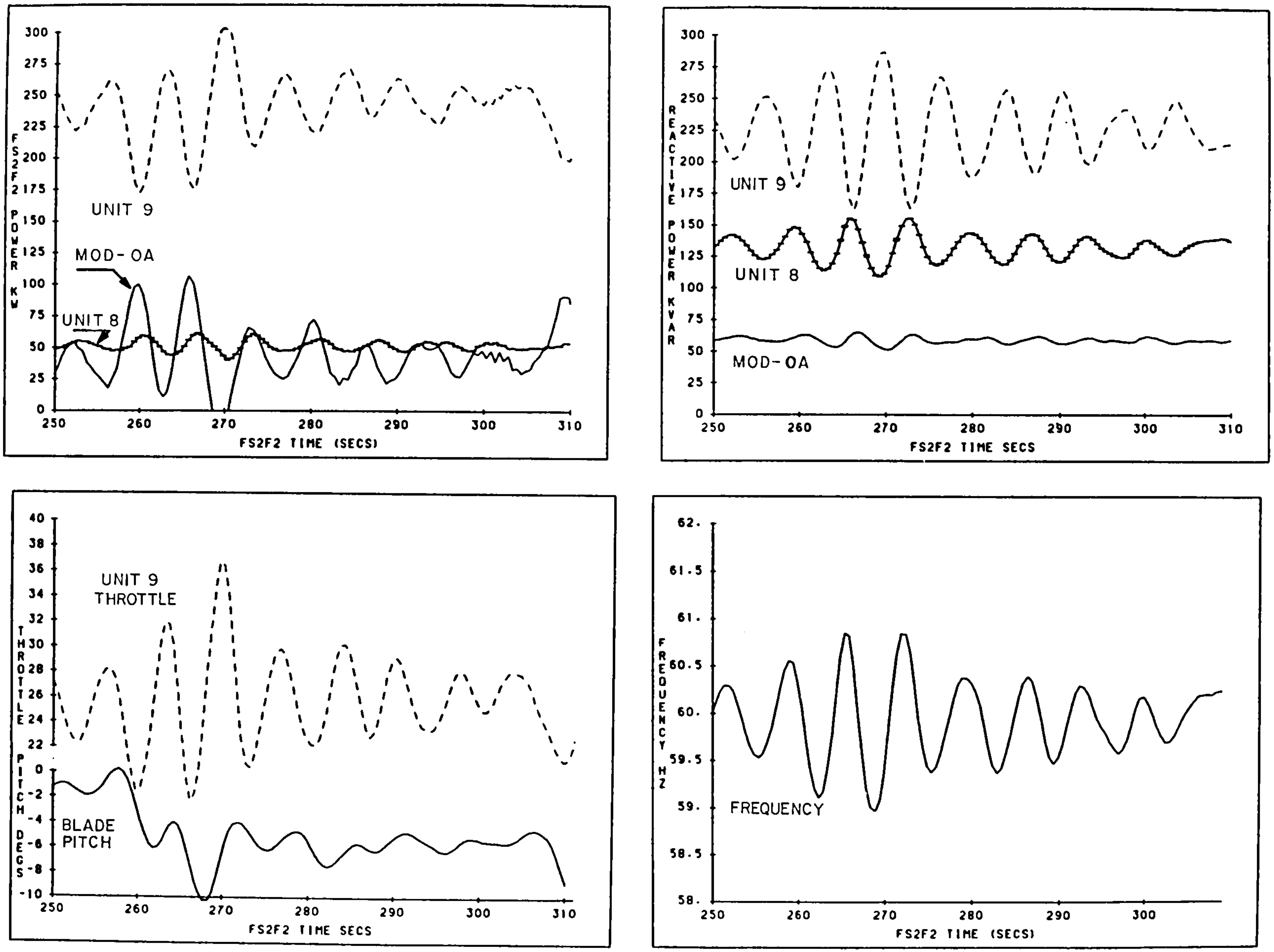


Figure 5-16. System Response During Pitch Control (50 kW Power Setpoint) Tower Shadow Effect Filtered Out for Clarity.

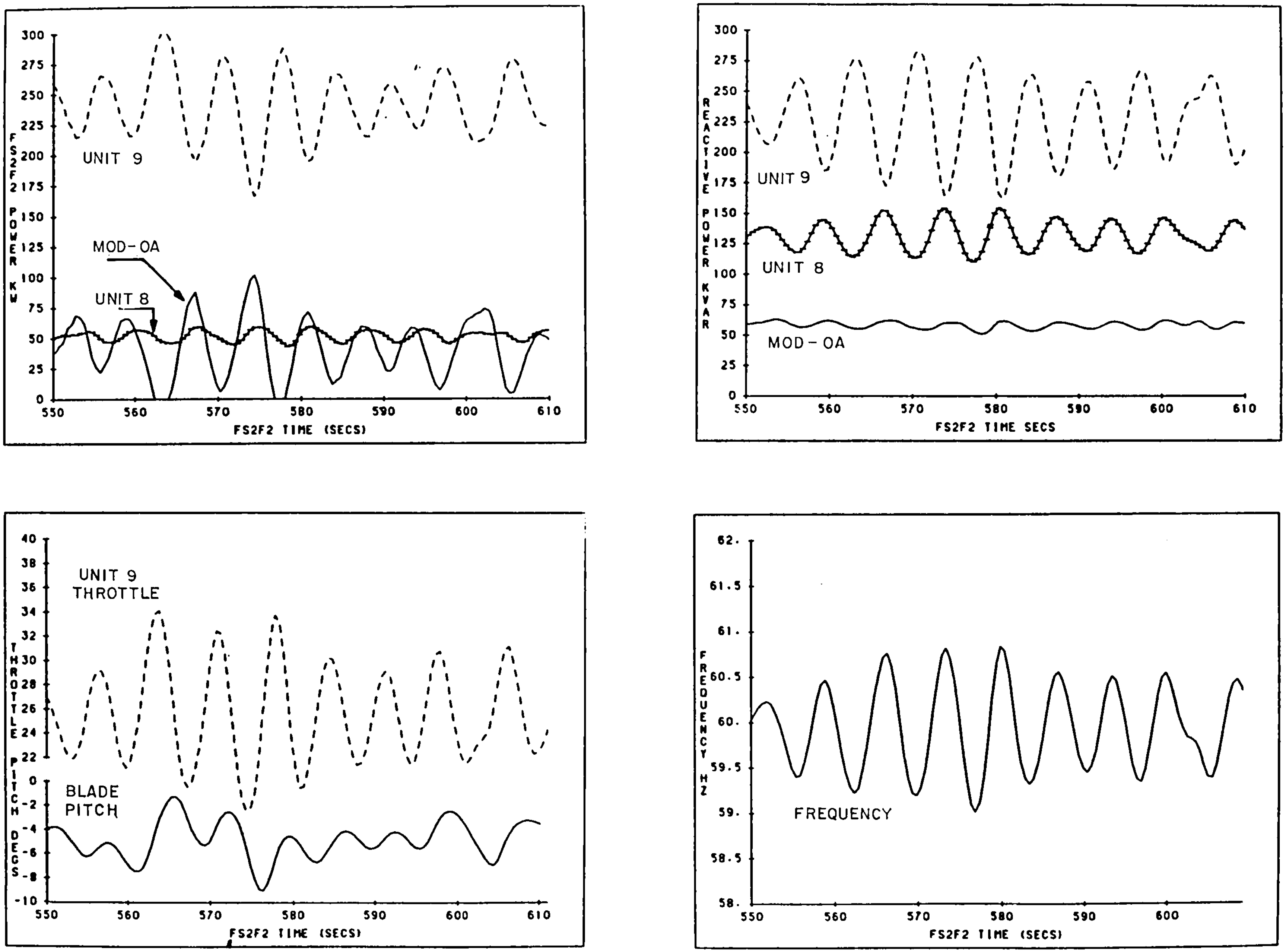


Figure 5-17. System Response During Pitch Control (50 kW Power Setpoint) Tower Shadow Effect Filtered Out for Clarity.

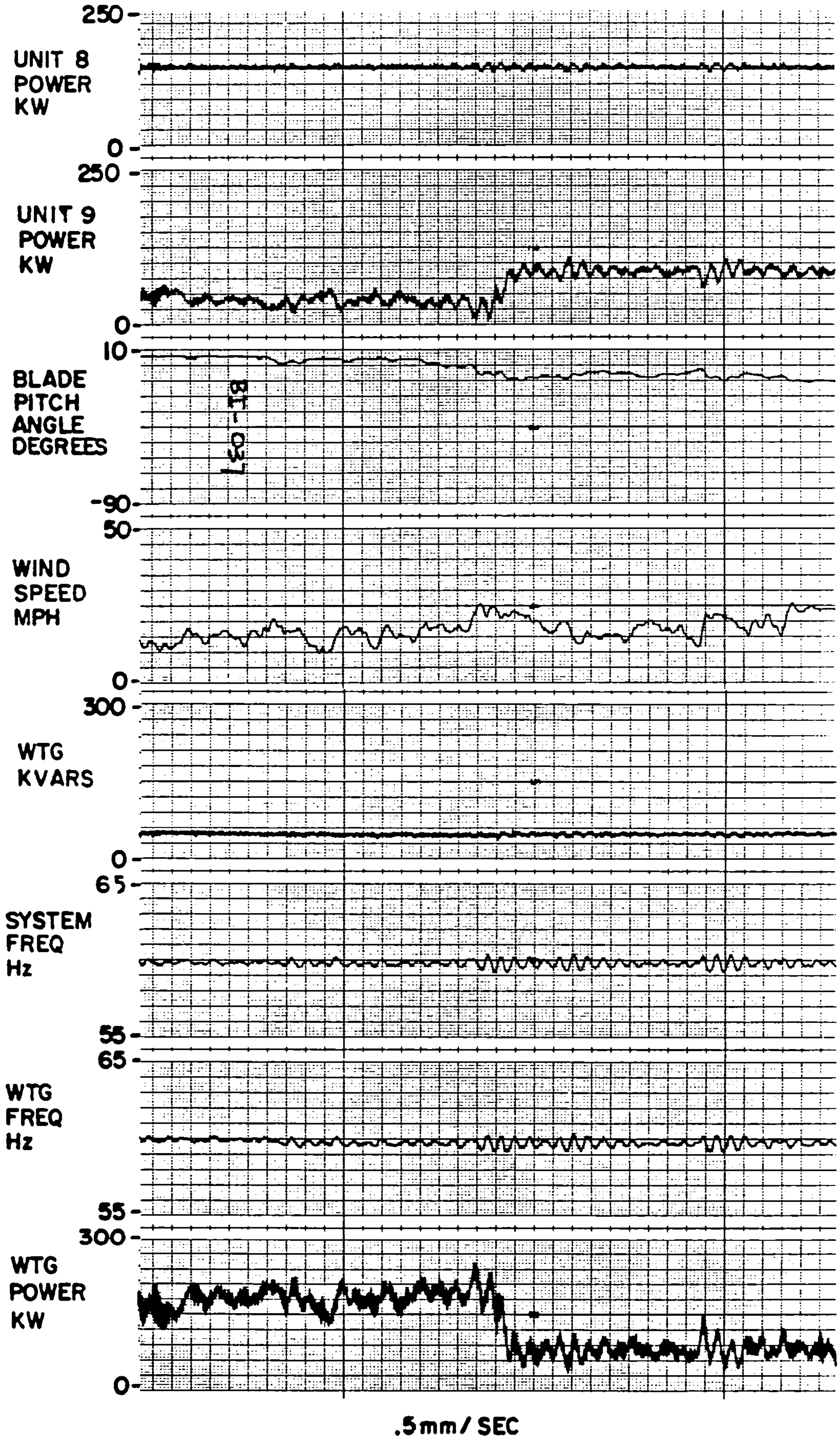


Figure 5-18. Power Setpoint Change 150 kW-50 kW

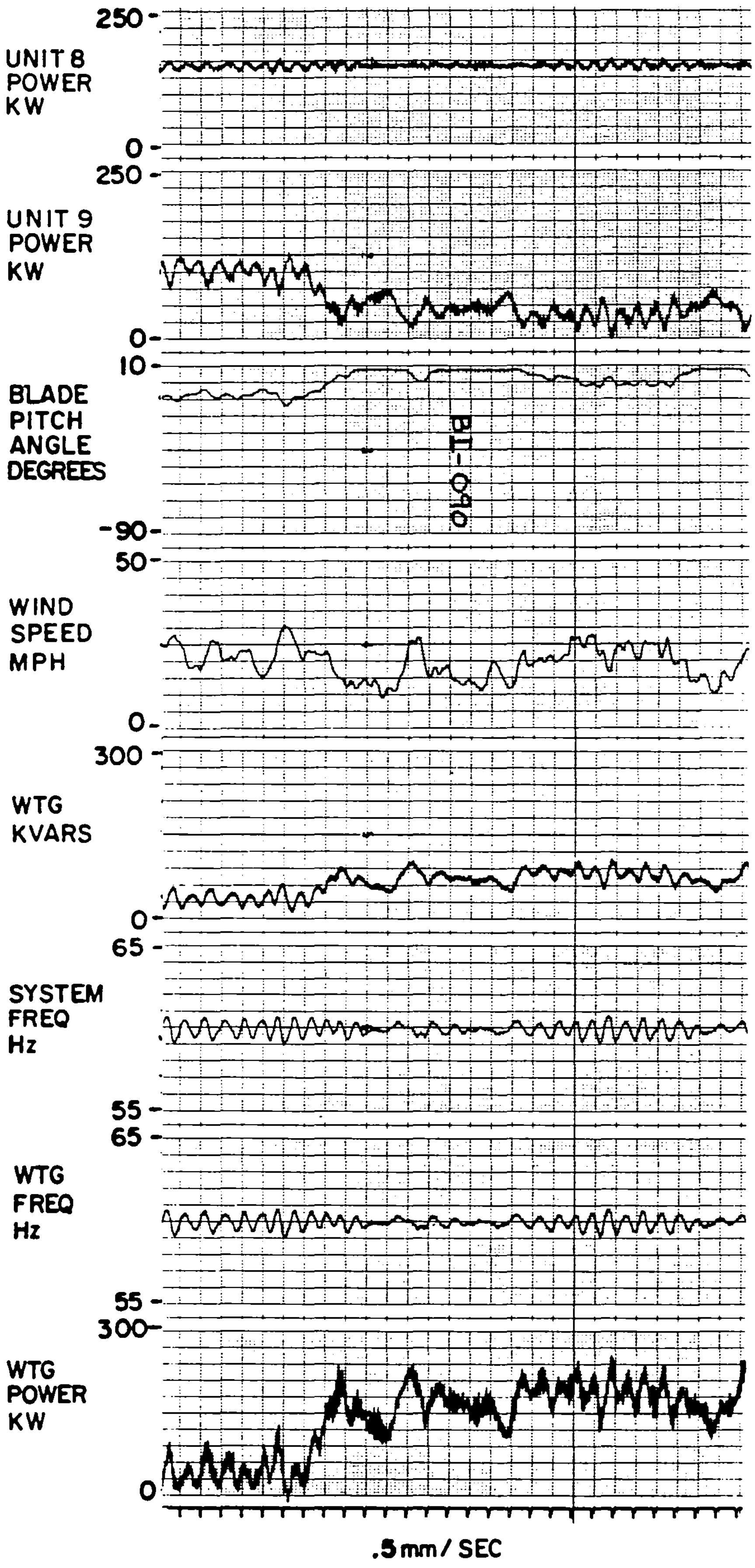


Figure 5-19. Power Setpoint Change 15 kW-150 kW

setpoint rather than any inherent difference due to the 50 KW setpoint -- as confirmed by the expanded run appearing in Appendix B (B-15). For the initial part of the interval, where the average WTG power is 150 KW, the 20 to 25 mph wind speed requires the blade pitch control to be active; here the peak-to-peak power frequency variations are also about 1 Hz. Wind speed decreases, operation goes to fixed pitch and the peak-to-peak frequency variation are reduced by a factor of 2 or 3 to 1.

In Figure 5-19, another transition in power setpoint is imposed -- this time between a very low (some 15 kW) and 150 kW setpoint. Wind conditions over the interval are more gusty than for the case of Figure 5-18 with the result that the peak-to-peak frequency variations reach about 1.8 Hz. However, as was the case in the previous example, there is little difference between the low and high power setpoint oscillation amplitude.

The tentative conclusion reached is therefore that the low frequency oscillation (.9 rad/s) in proportionally related to wind variational activity and negligibly related to the WTG power setpoint.

5.3 Linear Model of the Block Island System

In an attempt to address the low frequency (.9 rad/s) component that is most prevalent in those responses of the previous section where the blade pitch control is active, a linearized model is developed based in part on actual data measurements. Table 5-1 is a compilation of amplitude and phase measurements made on the dominant low frequency mode. In summary, these graphical measurements indicate that the pitch angle lags the MOD-OA power by 110° to 130° during these oscillations. The predicted pitch control phase lag during a 0.9 rad/s oscillation is 80° based on the specified pitch control transfer function. The conceptual system model is presented in Figure 5-12. The inertia of the diesels and the load have been lumped together. The unit #9 governor

TABLE 5-1

DYNAMIC INTERACTION DATA SYNOPSIS

MOD-OA STATUS	Figure Number	Power Setpoint kW	Sample Rate sec.	Moving Average sec.	Interaction of Interest	Oscillation Frequency rad/sec.	Oscillation Period sec.	Amplitude and Phase Angle: Sys. Freq. Hz	Power kW	Throttle deg	Pitch deg
Disconnected	5-1	0	0.5	1.5	Diesel Response to Load	0.97	6.5	0.13	9	0.9	-
	5-2	0	0.5	1.5	Diesel Response to Load	0.94	6.7	0.37	11	2.4	-
Start-Up	5-3	150	0.1	0.1	Synchronization	28	0.22	0.00	17	NA	0
					Tower Shadow Effect	6.6	0.95	0.06	20	NA	0
					Fixed Pitch	0.79	8.0	0.50	8 kW/s	NA	0.9 deg/s
Shut-Down	5-7	150	0.1	0.1	Tower Shadow Effect	6.6	0.95	0.08	32	NA	0
					Power Down	0.71	8.8	0.90	-15 kW/s	NA	-0.9 deg/s
Fixed Pitch	5-11	150	0.5	1.5	Wind Gust Interaction	0.63	10.0	$0.38\angle 0^\circ$	$26\angle -45^\circ$	$2.7\angle 117^\circ$	0
Pitch Control	5-12	150	0.5	1.5	Gov-Pitch Interaction	0.82	7.7	$0.34\angle 0^\circ$	$13\angle -26^\circ$	$3.4\angle 131^\circ$	$1.1\angle 23^\circ$
" "	5-13	150	0.5	1.5	" "	0.79	8.0	$0.70\angle 0^\circ$	$40\angle -34^\circ$	$5.5\angle 136^\circ$	$1.7\angle 29^\circ$
" "	5-14	150	0.5	1.5	" "	0.80	7.8	$0.77\angle 0^\circ$	$36\angle -36^\circ$	$4.7\angle 129^\circ$	$1.8\angle 39^\circ$
" "	5-15	150	0.5	1.5	" "	0.75	8.3	$0.73\angle 0^\circ$	$25\angle -20^\circ$	$4.0\angle 127^\circ$	$1.3\angle 46^\circ$
" "	5-16	50	0.5	1.5	" "	0.92	6.8	$1.0\angle 0^\circ$	$47\angle -38^\circ$	$7.3\angle 140^\circ$	$2.1\angle 38^\circ$
" "	5-17	50	0.5	1.5	" "	0.94	6.7	$1.6\angle 0^\circ$	$66\angle 32^\circ$	$11.8\angle 131^\circ$	$2.2\angle 43^\circ$
					Average Gov-Pitch Interaction	0.83	7.6	$0.86\angle 0^\circ$	$38\angle -31^\circ$	$6.1\angle 132^\circ$	$1.7\angle 36^\circ$

and throttle compares the system speed (frequency) to a reference speed (60 Hz) and compensates for speed error by changing the fuel rate (ΔP_F). The MOD-OA inertia moves at a different speed (ω_2) and is separated from the diesel system by the fluid coupling. Power delivered to the diesel system from the wind turbine generator is assumed to be equal to the power transmitted through the fluid coupling, that is, the generator's inertia and transient response are neglected. The pitch control, when active, compares the generated power to P_{max} (the power setpoint) and compensates for power error by changing the blade angle and thus the mechanical power.

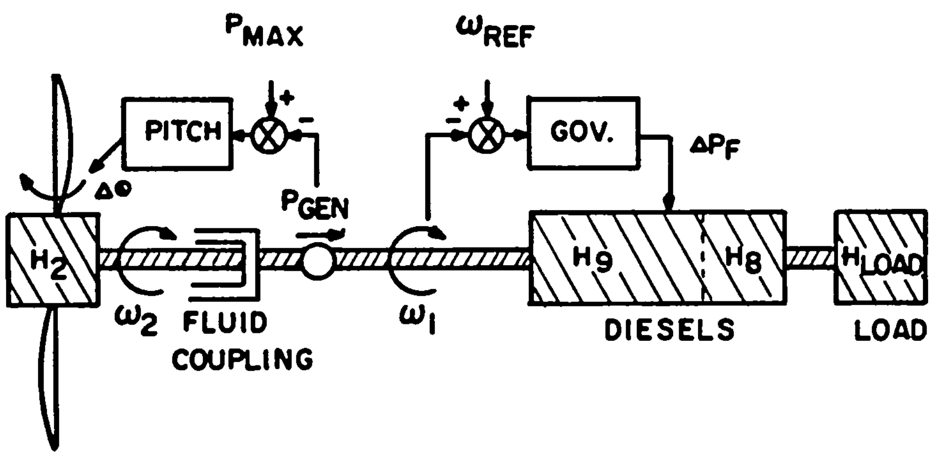


Figure 5-20. Conceptual System Model

5.3.1 System Transfer Functions

Per unit designation is used where possible with all quantities on the base of 250 kVA. The inertia constants used in this analysis are given below where H is the per unit kinetic energy of the rotating inertia in multiples of 250 kW-second. Additional data on the inertia constants of the diesel units and the MOD-OA are given in Appendix Table C2.

Machine	H Constant (kW-s/250 kVA)
Unit #8	1.24
Unit #9	6.0
Unit #10	7.0
MOD-OA	
Blades and gears	3.52
Generator, pulleys, belts	0.26
Loads	1.2

Under steady-state conditions and neglecting losses, the electrical power out of a generator is equal to the mechanical power (engine power) into the generator. However, during a disturbance in which the load changes, the changed power output of the generator will not initially match the mechanical power. The resulting difference in power will change the speed of the machine at a rate proportional to the mismatch. The per unit accelerating power is given by:

$$P_{acc} = P_{mech} - P_{gen} = 2\ H\ N\ \frac{dN}{dt} \tag{1}$$

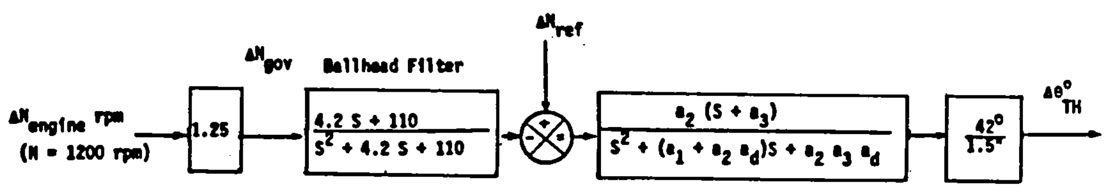
For small speed variations about the synchronous speed (N = 1) (1) gives the Laplace transform:

$$\frac{\Delta\ (P_{mech} - P_{gen})}{\Delta\ N} = 2\ H\ S \tag{2}$$

The result of this relationship in the Block Island system can be explained with a typical example. If units #8 and #9 are supplying the full system load, a sudden decrease in load will cause a simultaneous decrease in the total generated power. The mechanical power, however, will remain the same until the governor senses a frequency change. In the time interval before the governor reacts, the system frequency will begin increasing at a rate inversely proportional to the total rotating inertia on the system. The decrease in load will not be shared equally between the diesel units. Initially unit #8 will decrease only about one-sixth of the load change due to its smaller inertia with unit #9 dropping the remainder of the load loss. In addition, within a few seconds after the load loss, the unit #9 governor action will have resulted in correcting unit #9 to the new load change and restoring unit #8 to its original constant power output setting.

The speed governor on unit #9 controls the throttle angle which in turn controls fuel and mechanical power. The governor has response adjustments which were not changed during the study period. The speed droop modeled was zero which allowed the governor to control for 1200 rpm/60 Hz at all power loads resulting from varying wind turbine generator output.

The general form of the transfer function for the unit #9 governor is:



where a_1 = 26.6 to 87.8 adjustable

a_2 = 0.2902

a_3 = 0 to 8.26 adjustable

a_d = 0 to 86.8 = 0% to 5% droop (set at zero on Block Island diesel units)

The Ballhead Filter is neglected for frequencies in the 0.5 to 4 rad/sec range. The adjustments $a_1 = 40$ and $a_3 = 1$ were chosen to fit the data at 0.9 rad/s, resulting in the simplified transfer function:

$$\frac{\Delta\Theta^{o}TH}{\Delta f\ (Hz)} = \frac{-\ 203.1\ (S + a_3)}{S\ (S + a_1)}$$

and letting $a_3 = 1$ and $a_1 = 40$ yields

$$\frac{\Delta\Theta^{o}TH}{\Delta f\ (Hz)} = -\ \frac{5.08\ (S + 1\ )}{S\ (\frac{S}{40} + 1)}$$

The unit #9 throttle angle controls fuel and therefore mechanical power at the rate of:

$$\frac{\Delta P_F(kW)}{\Delta\Theta^{o}_{TH}} = \begin{array}{l} 13.5 \text{ at } 250 \text{ kW} \\ 10.2 \text{ at } 50 \text{ kW} \end{array}$$

13.5 kW/Deg is used for this report resulting in the following per unit transfer function:

$$\frac{\Delta P_F}{\Delta\omega_1} = \frac{-16.5\ (S + 1)}{S\ (\frac{S}{40} + 1)} \tag{3a}$$

Two modifications in the model of the governor transfer function were utilized in evaluating the effect of governor adjustments that would dampen the system oscillation during MOD-OA pitch control.

Slowed response modification:

Letting $a_3 = 0.S$ and $a_1 = 30$ yields the per unit transfer function

$$\frac{\Delta P_F}{\Delta\omega_1} = \frac{-11\ (2S + 1)}{S\ (\frac{S}{30} + 1)} \tag{3b}$$

5% droop modification

Letting a = 86 yields for the per unit transfer function

$$\frac{\Delta P_F}{\Delta \omega_1} = \frac{-16.5\ (S + 1)}{\frac{S^2}{40} + 1.63\ S + .628}$$

The inertia of the MOD-OA blades and gears is connected loosely to the Block Island system through the hydraulic fluid coupling.

The fluid coupling transfers the power from the turbine and gears to the generator. For the Gyrol 550 fluid coupling at 1400 rpm, the power transfer is given empirically by:

$$P = 25.8\ N_s - 168.3\ N_s^2 \qquad (4)$$

where the slip is $N_s = (N_{rotor} - N_{gen})$ and the linearized transfer function is:

$$\frac{\Delta P_{rg}}{\Delta N_s} = 25.8 - 336.6\ N_s \qquad (5)$$

$$= 23.0 \text{ p.u. at } 50 \text{ kW}$$
$$= 19.9 \text{ p.u. at } 100 \text{ kW}$$
$$= 16.2 \text{ p.u. at } 150 \text{ kW}$$

The blade pitch angle on the MOD-OA is set by the microprocessor controller to maintain constant maximum power. The maximum power set point (P_{max}) may be adjusted on the Block Island machine from 25 to 150 kW as deemed necessary by BIPCO personnel. During the time periods when the wind provides less energy than the power set (P_{max}) the pitch angle is fixed at 0^o (where -90^o is the fully feathered position at shutdown). With the blades at a fixed pitch angle, the power output fluctuates with the wind speed. When the power output exceeds P_{max}, the pitch control becomes active to control for constant P_{max} power output. The specified transfer function programmed in the microprocessor controller contains a proportional coefficient (0.021 Deg./kW) plus an integral coefficient (0.04 Deg./kW. -Sec.):

$$\frac{\Delta\Theta^{o}\text{command}}{\Delta(P_{max} - P_{gen})} = 5.25 + \frac{10}{S} \quad \text{programmed function} \qquad (6)$$

When the controller constants are adjusted for improved damping -- discussed in section 5.3.2 -- the transfer function that results is

$$\frac{\Delta\Theta^{o}\ \text{command}}{\Delta(P_{max} - P_{gen})} = 40 + \frac{4}{S} \qquad (7)$$

The response of the hydraulic pitch actuator on an identical wind turbine was measured by NASA LeRC over the frequency range 2 to 40 rad/sec. For this range, the response can be approximated by:

$$\frac{\Delta\Theta^{o}\ \text{pitch}}{\Delta\Theta^{o}\ \text{command}} = \frac{1\angle -15^{o}}{(.029\ S)^{2} + .041S + 1}$$

For the purposes of this study, the measured response was extrapolated to 0.5 rad/sec and the additional 15^{o} phase shift incorporated in the following approximate transfer function:

$$\frac{\Delta\Theta^{o}\ \text{pitch}}{\Delta\Theta^{o}\ \text{command}} = \frac{1.25}{(.029\ S)^{2} + .041\ S + 1} \cdot \frac{(1 + .6\ S)}{(1 + S)} \qquad (8)$$

for S = 0.5 to 6 rad/s

Analysis of the actual pitch control response during the 0.9 rad/s oscillation revealed an inconsistency with the expected response based on the programmed integral-plus-proportional pitch control and the hydraulic actuator response. The expected pitch response to a 0.9 rad/s variation in output power calls for the blade pitch to lag the power error (P_{max} - P_{wtg}) by 80 degrees. The actual response was found to be lagging the power error signal by 110 to 130 degrees. The cause of this additional 48 degree phase lag is not known from the available pitch data or from simulation of the microprocessor controller. For the purposes of correcting the pitch transfer function, for the actual data, a correction function was used of the form:

$$\frac{\Delta\Theta^{o}\ \text{pitched-mod}}{\Delta\Theta^{o}} = \frac{1.4}{1 + S} \qquad (9)$$

This function approximates the system for oscillations in pitch angle in the frequency range of the observed 0.9 rad/s oscillations.

The transfer functions of the major elements of the Block Island system are shown in the system model of Figure 5-21. The response of the MOD-OA power output and system frequency to a 100 kW step change in wind power was analyzed for this system. The results are presented in the following two sections.

5.3.2 Modelled MOD-OA Response to Step Change in Wind Power

The modelled time response of the MOD-OA to a set change of 100 kW of wind power is shown in Figure 5-22. Under fixed pitch control on the Block Island system the power output has a rise time of 2 seconds and 6% overshoot. The rise time characteristic is effected mostly by the ratio of fluid coupling damping to WTG inertia. The higher the ratio the faster the response. The overshoot is determined by the system frequency fluctuation resulting from the direct response to the load decrease.

Activation of the pitch control results in an underdamped response with an exponential time constant of 10 seconds (95% settling time of 30 sec.). Although this is a stable response, the low damping allows the oscillation to continue on several cycles before damping out.

If the MOD-OA is connected to a much larger system (an "infinite" bus) the activation of pitch control results in a slightly underdamped response with a time constant of just 3 seconds (9.1 seconds settling time). Thus, the response of the Block Island diesel contributes significantly to the 0.9 rad/s oscillation recorded in the data.

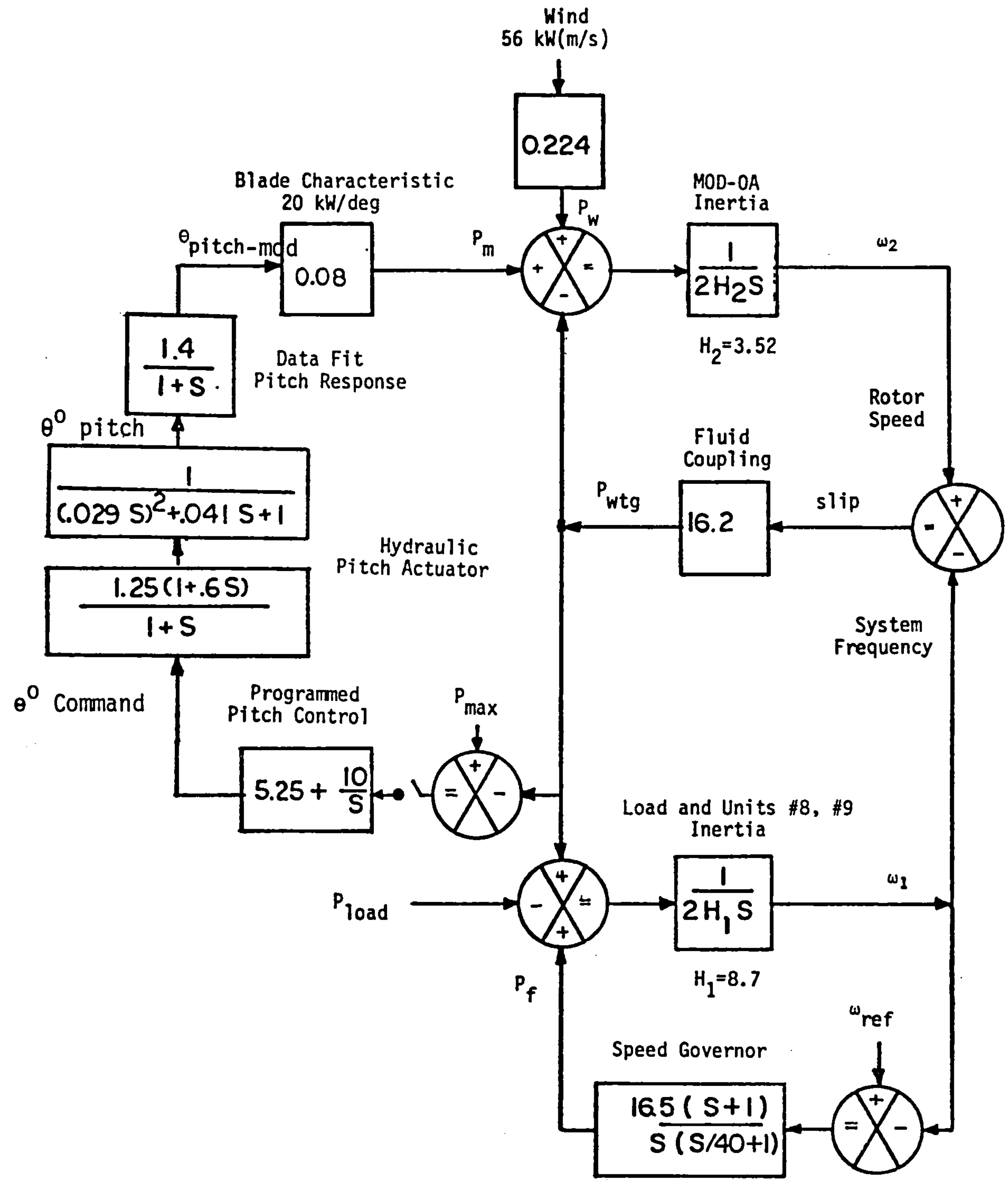


Figure 5-21. Block Island Dynamic Model (250 kVA per unit base)

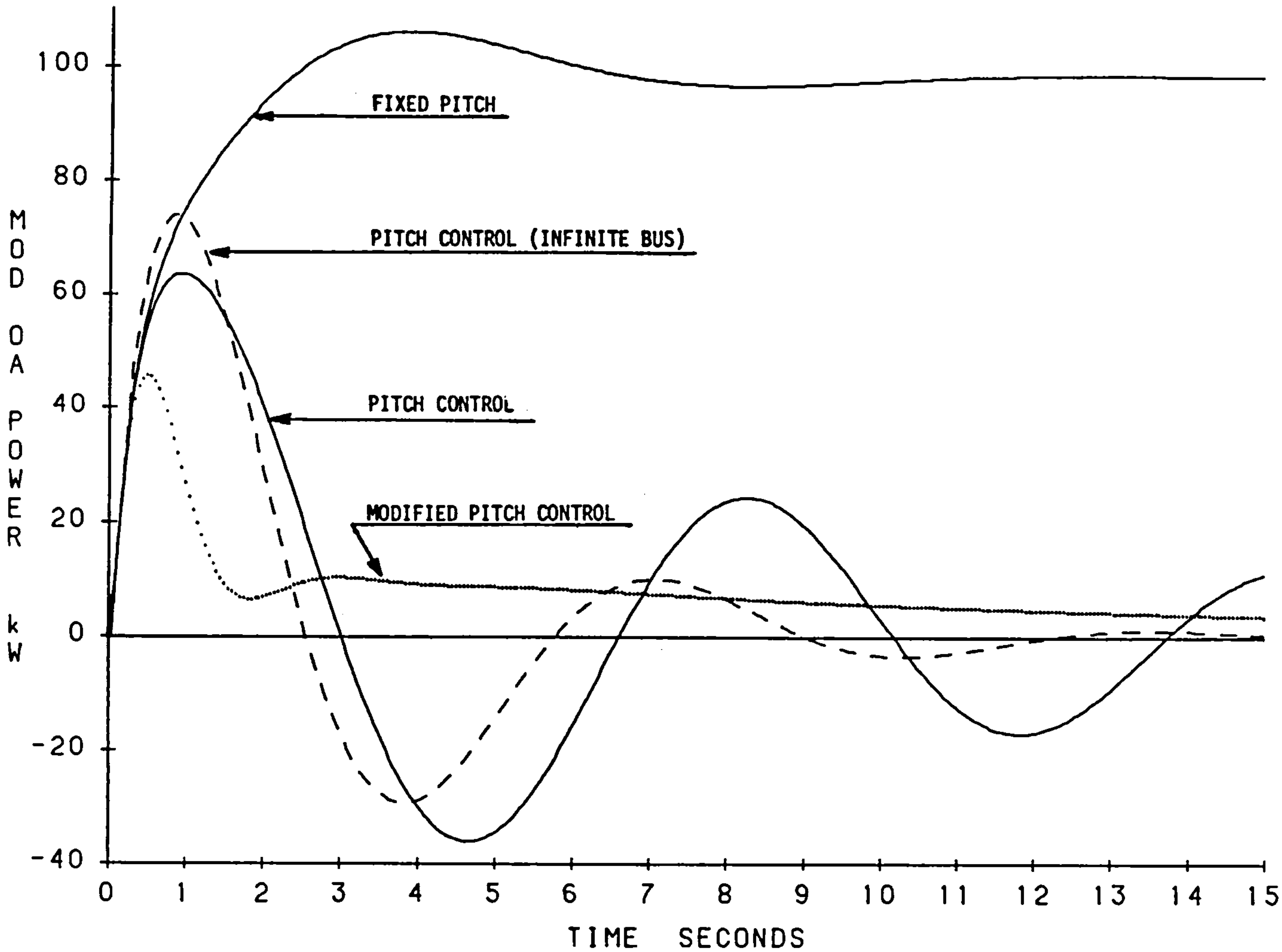


Figure 5-22. MOD-0A Response to 100 kW Step Wind Change on BIPCO System Model (Power Setpoint = 0KW)

The response of the MOD-OA with pitch control should be greatly improved by modifying the proportional and integral control gains stored in the microprocessor to give an over damped response. Figure 5-22 shows the effect of changing the programmed proportional and integral gains from those given in equation (6) to those of equation (7). The result of the modified pitch control on the Block Island system has a time constant of 2.3 sec (7 second settling time) an improvement over the present pitch control and the fixed pitch response. Further analysis will need to be performed on a modified pitch control to investigate its effect on blade stress and on the response to the tower wind shadow effect.

5.3.3 Modeled Block Island System Response to a Step Change In Wind Power

The characteristic roots of variations on the Block Island model are shown in Figure 5-23. The Block Island diesel system with no modifications and the MOD-OA off has a damping ratio (ζ)* of 0.48 at a natural frequency of .98 rad/s. This is the same natural frequency of the MOD-OA with pitch response on an infinite bus. The combination of the MOD-OA on the Block Island systems results in a natural frequency of 0.88 rad/s and the low damping ratio of 0.11. Modification to the diesel governor to slow its response or by adding 5% droop has the effect of increasing the damping of the system during MOD-OA pitch control. Modifying the pitch control has a greater the effect by bringing the response of the system with the MOD-OA back to the response of the diesels with no MOD-OA connection.

The time response of the system frequency to a 100 kW step change in wind power can be seen in Figure 5-24. The largest oscillation amplitude occurs for the unmodified pitch control of the MOD-OA.

*Definitions relating to characteristic root $\sigma \pm j\beta$ damped natural frequency - β; undamped natural frequency - ω_n; damping ratio

$$\zeta = \frac{\sigma}{\sqrt{\sigma^2 + \beta^2}} \quad ; \quad \omega_n = \sqrt{\sigma^2 + \beta^2}$$

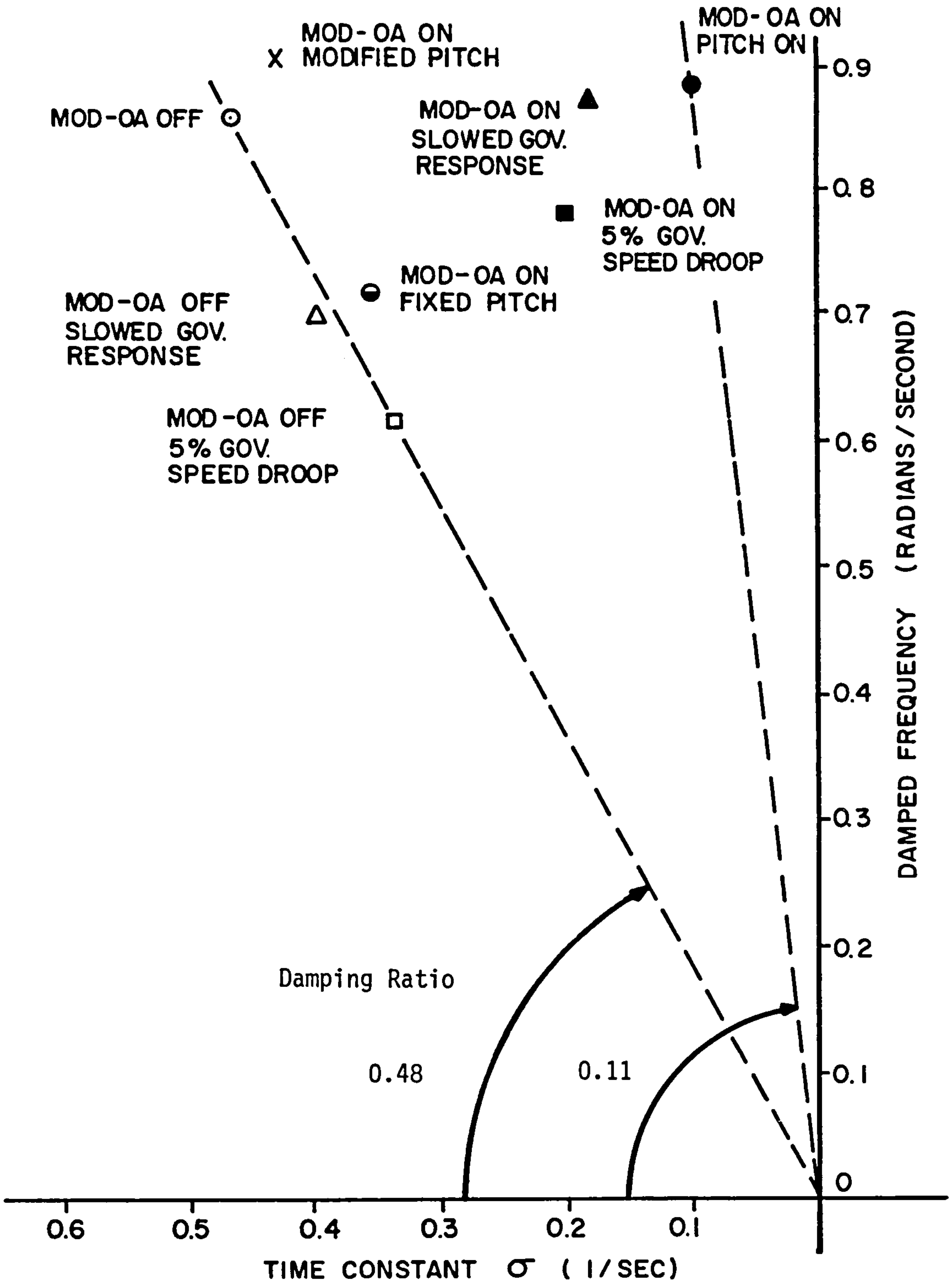


Figure 5-23. Position of the Characteristic Root for Variations of the BIPCO Model

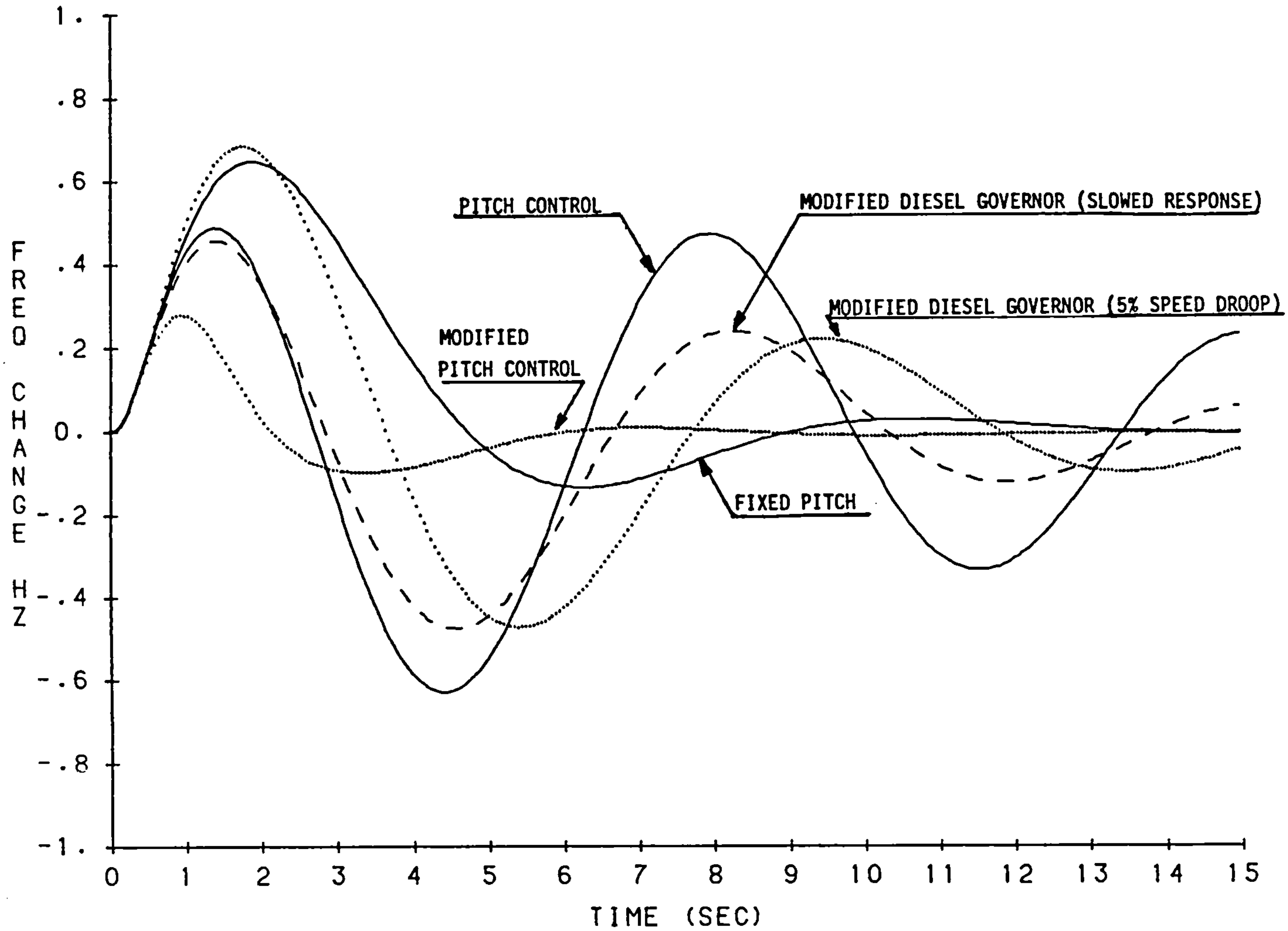


Figure 5-24. Synchronous Frequency Response to 100 kW Step Wind Change on Variations of the BIPCO System Model

Damping can be introduced by modifying the governor gains or by adding 5% speed droop. The most significant damping is achieved by modifying the pitch control. The time response for the MOD-OA with no pitch control is also shown for comparison.

5.4 Dynamic Interaction Conclusions

Power and voltage transients due to MOD-OA startup and normal shutdown did not significantly disturb the system.

Cyclic power variations due to blade-tower shadow effect did not significantly disturb the system.

MOD-OA operation under fixed pitch control caused power fluctuations which were successfully counteracted by the diesel governor control. The resulting variation of the synchronous frequency were of the same magnitude as some hourly load fluctuations.

MOD-OA operation under constant power variable blade pitch control resulted in an amplification of the natural period of the system. The resulting oscillation usually caused a 1% cyclic frequency variation with a period of seven seconds. The amplitude of this .9 rad/s oscillation is found to be approximately proportional to the rms value of the wind speed fluctuation and is independent of the MOD-OA power setpoint.

A response analysis of the Block Island system model revealed the combination of the present pitch control and the BIPCO Unit #9 governor response to have a relatively low damping factor to system fluctuations. Damping was shown to be improved by modifying the governor settings and the programmed pitch control. Modifying the pitch control gains was shown to have the greatest effect by returning the damping factor of the Block Island system to nearly the same value as when the MOD-OA is disconnected.

The most extreme transient frequency disturbances reach 5% peak-to-peak under certain emergency shutdown conditions where WTG power was stepped from a high value to zero.

6. MOD-OA VOLT-AMPERE REGULATION MODES

The objective of the volt-ampere regulation study was to evaluate the three modes of operation of the MOD-OA voltage regulator. The three modes of regulation are constant volt-amperes reactive (var), constant power factor control (PF), and constant voltage. The MOD-OA operated successfully in all three modes. Normal MOD-OA operation calls for constant 60 kVAR regulation. One month after the study period began, the regulation was changed to constant 85% power factor. At the end of the study period, a constant voltage regulation test was conducted over a 4-hour period.

Normal voltage regulation on Block Island is accomplished by operating a diesel with auto speed governor and auto voltage regulation settings. The other diesels will have their regulators switched to manual to supply a relatively constant field voltage to the rotors. In contrast, the MOD-OA regulator is not set on manual, rather it is continuously controlling the field current for constant var or PF output.

Figure 6-1 is a block/single line diagram that functionally describes the typical BIPCO system configuration during the three-month data instrumentation and collection period with emphasis on the WTG

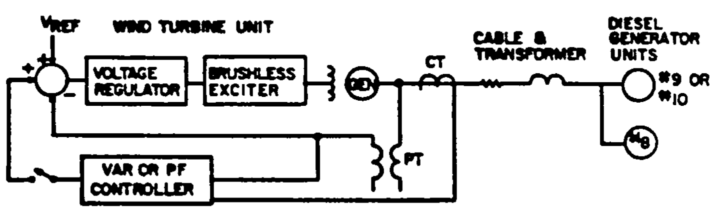


Figure 6-1 - Basic Configuration for Study of Excitation Control on MOD-OA WTG excitation components. The MOD-OA wind turbine generator is a salient pole type whose field is driven by a brushless rotating exciter; the stationary field winding of the latter is in turn powered by a solid-state regulator which includes an adjustable damping feedback circuit. An additional module incorporates the selectable var or PF control action.

6.1 Constant Reactive Power (Var) Control

Constant reactive power was determined to be the the most desirable operating mode for wind turbine regulation during early design studies. The major reason for this is to insure sufficient stabilizing generator torque during wind gusts at low power output.

This control method can assume one of several schemes in accomplishing its stated objective. For example, by removing the terminal voltage feedback signal to the regulator and replacing it with a signal proportional to the reactive power, the latter may be controlled statically or dynamically. Another technique -- the one actually used -- consists of inserting a voltage in series with the voltage reference. Here, the terminal voltage feedback signal is unaltered and an integral reset control changes the reference until the actual reactive power exactly matches the desired setting in steady-state.

Figure 6-2 reveals how well the WTG MOD-OA reactive power is controlled to the 50 kvar setpoint. Also, it is apparent that the controlled diesel (Unit #9) supplies the var fluctuations resulting from terminal voltage variations. Another aspect of reactive power behavior is that the fixed excitation diesel generator (Unit #8) exhibits var fluctuations 180^{0} out of phase with those of Unit #9; so that although Unit #8 is supplying a fixed level of vars to the system, it is absorbing a portion of the variational contribution from Unit #9. In effect then, the larger number of generators with fixed excitation, the greater the burden on the controlled unit from a transient or variational standpoint. As shown in Figure 6-2, generators under constant var control have the advantage of not affecting this fluctuating var component.

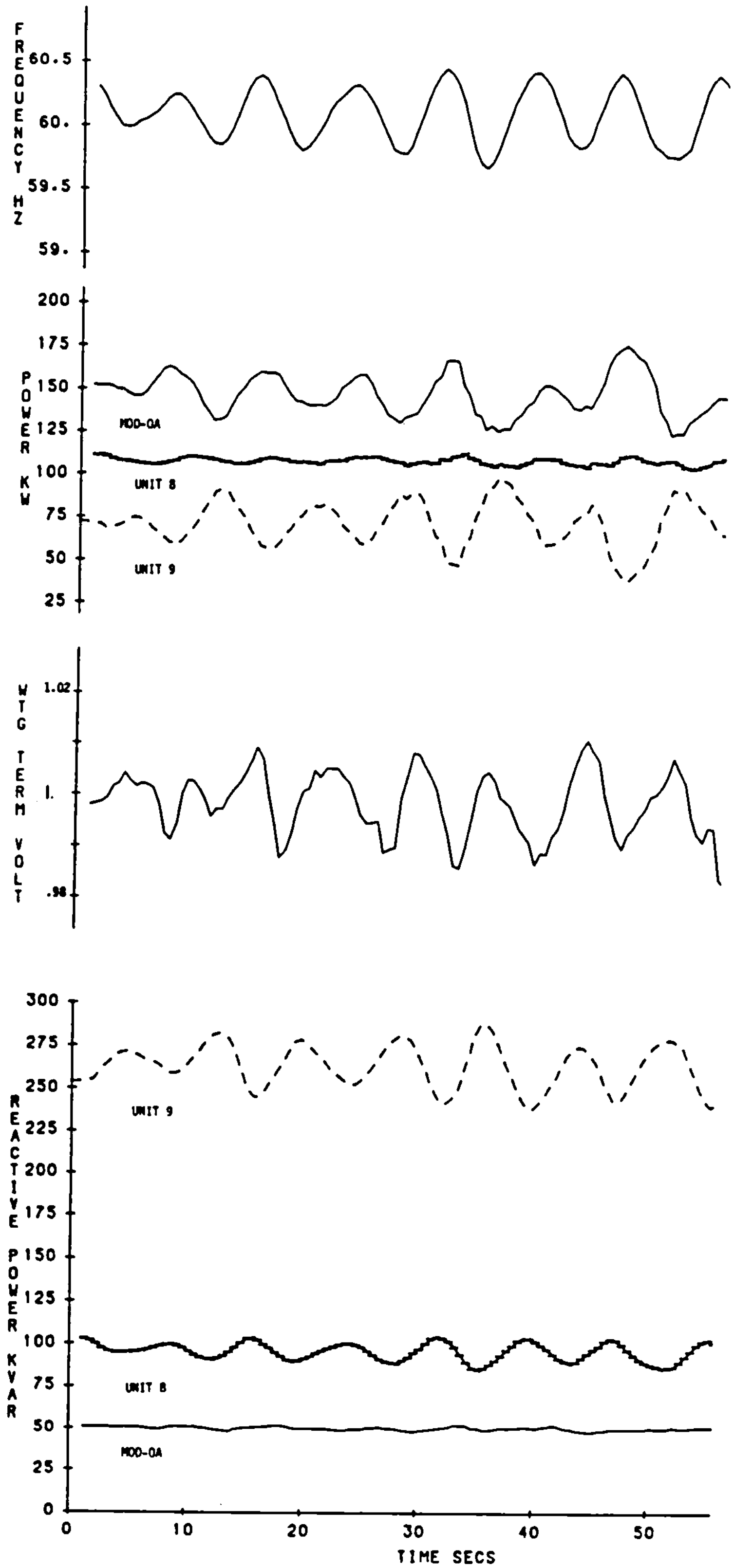


Figure 6-2. Measured Performance with MOD-OA WTG under Constant Reactive (Var) Control

The data shows the MOD-OA constant reactive power mode contributes to the reactive power requirements of the system while not significantly affecting voltage control by the load diesel generator. During the 0.9 rad/s oscillations, the variation in MOD-OA reactive power was significantly less than the reactive power variation in unit #8 which was operating with fixed excitation.

6.2 Constant Power Factor Control

Constant power factor control allows the reactive power to vary in direct proportion to real power. The power factor (PF) is the ratio of real power to total volt-amperes and is related to reactive power by the following:

$$\text{Reactive Power (kVAR)} = \sqrt{(\text{kVA})^2 - (\text{kW})^2} = \text{kW}\sqrt{\frac{1}{\text{PF}^2} - 1}$$

On March 1, 1982 the MOD-OA was switched to constant power factor control for a 12 week period. The 0.85 pf setting provided for a reactive power variation of 0 to 93 kVAR over a range of 0 to 150 kW output. For a nominal system with non-excessive var requirement (i.e., the lagging power factor load is relatively low), maintaining constant power factor WTG operation would be the most desirable method of excitation control from the standpoint of the effect the WTG generation has on the diesel system. That is, under constant power factor, the WTG appears to the diesel generator as a (negative) fixed impedance load -- as such, this probably imposes the least severe loading constraints since ideally all generating units would be operating at their design power factors.

The method of control of power factor utilizes the same reset function used for var control. The difference is that rather than comparing with a constant reference, the reference is now proportional to the real power. Thus, the ratio of vars to power and hence power factor is maintained constant.

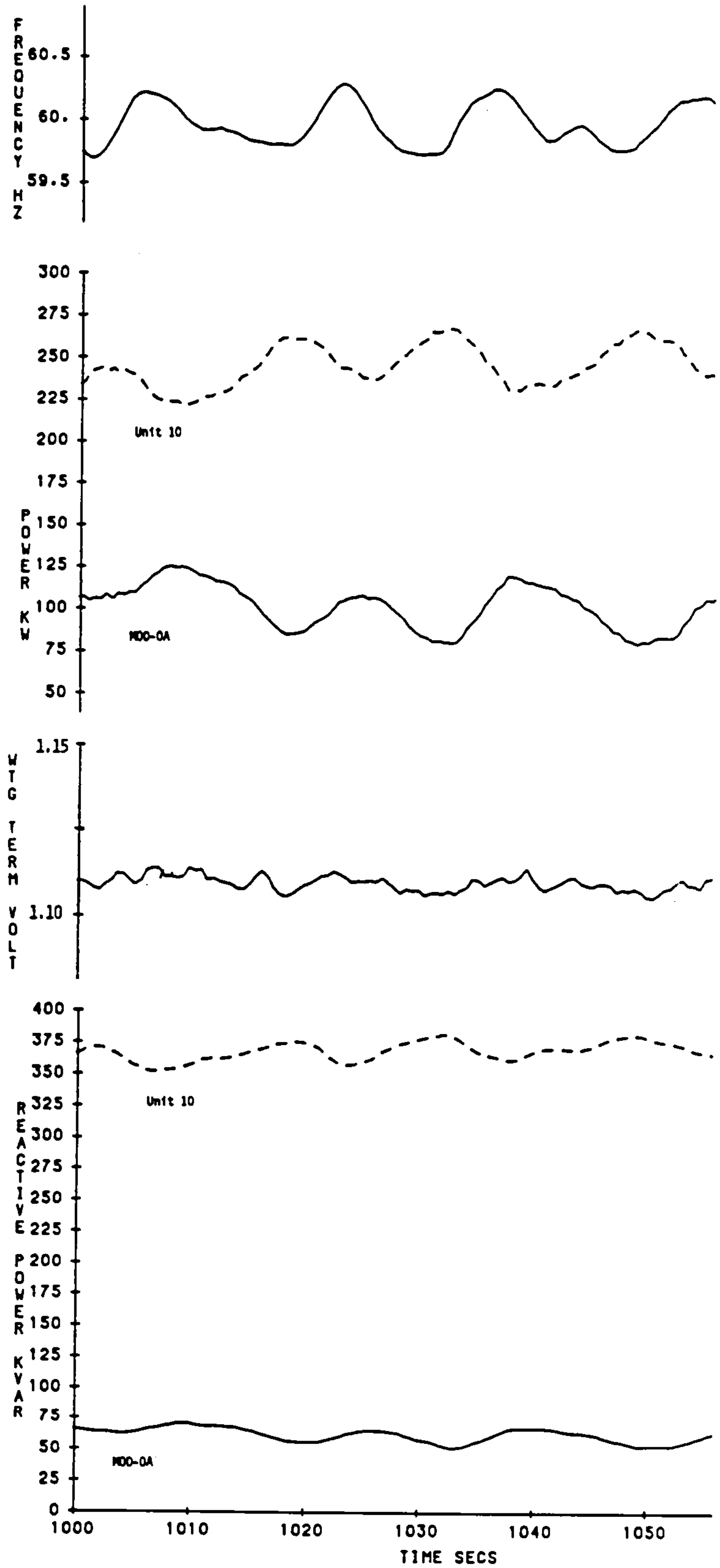


Figure 6-3 Measured Performance with MOD-OA WTG under Constant Power Factor (PF) Control

Figure 6-3 is typical of the behavior when the WTG excitation control is in the constant power factor mode. For this particular case, the MOD-OA is operating below the nominal 150 kV setpoint so the blade pitch is fixed. The wind profile during the 60 second segment produces WTG power fluctuations of the same magnitude (i.e., 30-40 kW) as in Figure 6-2. However, the reactive power variations are noticeably higher than in that case. Also, because Unit #10 is the only diesel generator connected, the variational var component due to a fixed excited generator is missing, and there is a corresponding reduction in the peak-to-peak var amplitude of Unit #10. If the ratio of WTG power to vars is calculated, it is found to have the same relative constant as vars did in Figure 6-2, denoting good control of power factor. Similar to Figure 6-2, the power and var fluctuations are in-phase and the peak-to-peak frequency variations are nearly the same.

An advantage that the constant PF control has over either the constant var or voltage control is that as the decreasing blade pitch angle reduces WTG electrical power to zero it also reduces the vars to zero. Thus when the breaker trips, the current interrupted is very small and therefore the system voltage transient is negligible. With either constant voltage or constant var control, the vars will not be zero at the zero power level. Although this does produce a voltage transient, similar to applying an inductive load on the system, it is generally the same amplitude as produced by normal system load activity.

6.3 Constant Voltage Control

The MOD-OA wind turbine has the capability of regulating the generator output voltage within a specific range. This range depends on the line impedance separating the wind turbine from other voltage regulating generators and on the value of the adjustable droop resistor in the voltage regulator. On Block Island, the low impedance of the line and transformer between the MOD-OA and the Block Bus Figure 3-4 results in a maximum voltage drop between these buses of about 1% with a wind turbine output of 250 kVA.

A problem with constant voltage control on any type of interconnected synchronous generators (WTG or diesel) is the relative inability to share proportionately the reactive power load. The situation is analogous to real power sharing unbalances that can occur when the speed governors on generators are at a low droop setting -- i.e. a low ratio of speed change to load change. By increasing the speed droop, real power load sharing can be improved. So it is with reactive load. This is achieved by introducing the additional feedback signal to the voltage regulator which is proportional to terminal current and lagging terminal voltage by 90^{o}. In effect, this acts as an inductive reactance placed in series with the generator, but lying outside the voltage regulator loop, so that reactive current is limited. This so-called reactive droop compensation has increasing importance as the impedance of the tie among generators decreases.

The dynamics of the voltage control loop -- formed by regulator/exciter and generator can also affect the system stability in terms of changing the damping of the system natural frequencies. It is found in general that, relative to fixed excitation (no voltage control), the faster the voltage regulator responds, the lower will be the damping of the system natural frequency. It is also possible to produce negative damping from some regulator/exciter designs that interact with the system's natural frequency.

Figure 6-4 shows behavior under constant voltage control with 5% reactive current droop compensation. Here, the wind activity has minimal gusting activity with the result that the dominant .9 rad/s oscillation is low. As a result, the var activity of the diesel generator is relatively low. Contrasted with the other two schemes, the WTG var fluctuations are seen in Figure 6-4 to be higher than those of the diesel generator. Also, the low frequency var and power oscillations are opposite in phase -- the major result of which is that the transient excitation requirements of the diesel unit are minimized.

Figure 6-5 serves to demonstrate how the characteristics of constant voltage control can ultimately lead to a deterioration in performance.

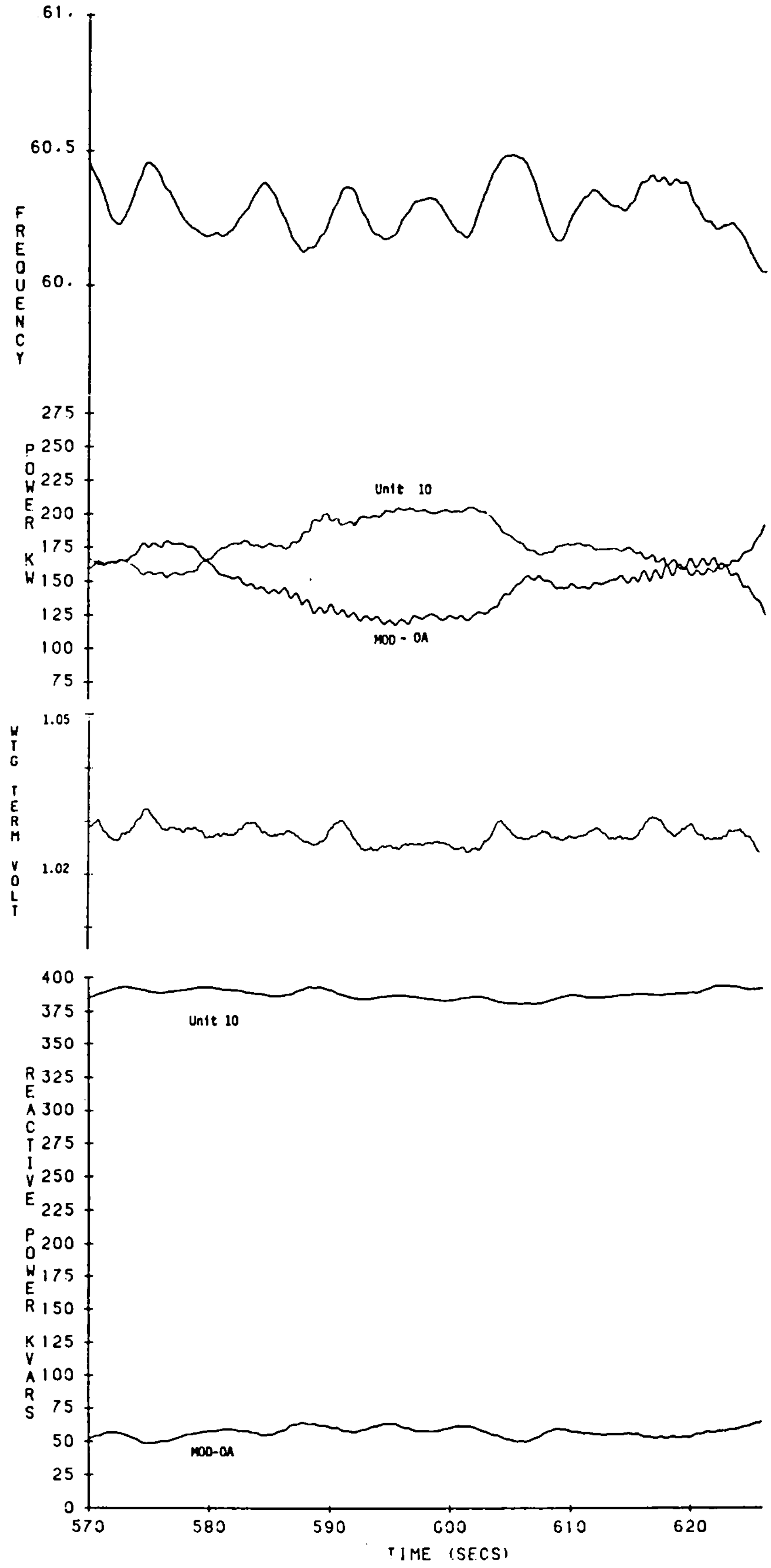


Figure 6-4 Measured Performance with MOD-OA WTG under Constant Voltage Control - 5% Droop Compensation

Here the droop compensation has been set to zero and as the wind speed rises producing WTG power above the 150 kV setpoint, the blade pitch control begins to reduce the power. As the combination of WTG dynamics and wind profile interact to produce a growing oscillation, the phase opposition between power and vars (at 0.7 rad/s) becomes evident. This is just the opposite desired condition from the standpoint of preventing loss of synchronism. Although the fluid coupling used in the WTG minimizes this problem, Figure 6-5 shows the potential for underexcited operation as the power swings become large. Therefore, uncompensated constant voltage control should probably be avoided.

Figure 6-5 also shows a shutdown operation -- increasing blade pitch gradually to bring the WTG power to zero. Now, because of the constant voltage control, the WTG excitation and vars are increasing, so that at the time when the line breaker opens, the WTG is delivering around 150 kvars. Dropping this generation appears to the diesel system to be equivalent to applying a 150 kvar inductive reactive load as evidenced by the drop in terminal voltage seen in Figure 6-5. The recovery of the voltage also illustrates the response of the diesel generation regulator/exciter control system.

The traces comprising Figure 6-5 are unfiltered and show the presence of the approximate 6 rad/s wind shadow frequency in the WTG power. The WTG vars trace evidences the 6 rad/s frequency, but at an amplitude less than 30% of that visible on the power trace.

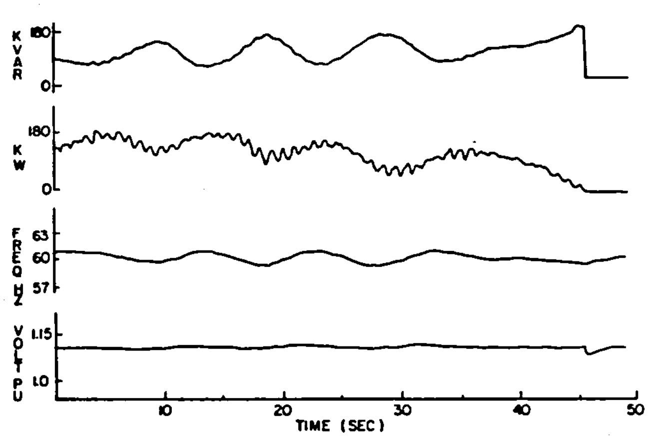


Figure 6-5 Measured Performance with MOD-OA WTG under Constant Voltage Control - 0% Droop Compensation - Manually Initiated Shutdown of WTG

6.4 Simulation Model Investigation

In examining the foregoing field measurement results, it is difficult to compare and quantify the effect on system voltage and frequency as a function of the type of excitation system alone. A transient (time domain) model of the system block diagram given in Figure 6.1 was therefore formulated and digitally programmed using constants developed by the equipment manufacturers and given in operational form on Figure 6-6. In Appendix C3 appear the per unit reactances and time constants incorporated into the model. The diesel generators were lumped together and represented by a fixed voltage in series with their equivalent transient reactance. This simplified model for the diesel generators was justified primarily on the basis that no evidence of interaction due to the diesel generator excitation system was observed in the data.

For the mechanical portion of the simulator model, it was found convenient to use the model developed in section 5. Figure 6-7 shows how that model has been modified. Here, torque quantities rather than power quantities are used and, rather than assuming power and/or torque on the output side of the fluid coupling to be identical to WTG electrical power and/or torque, the latter is now a function of the electrical dynamics of the WTG. Also, the previous model lumped the moments of inertias of the blades, hub, gears, pulleys, and input side of the fluid coupling into a single value. A mechanical modal analysis(19) gives a low, purely mechanical, modal frequency of approximately 20 rad/s for MOD-OA systems. Because the WTG ratio and output fluid coupling inertias are small, the modal frequency formed by these and the equivalent air gap torque spring constant is also in the 20 rad/s region. It, therefore, was deemed advisable to include the mechanical mode to determine if any interaction might occur between these two nearly equal modal frequencies. Two approximately equal inertia constants (H_a, H_b) and a single spring shaft constant K form this simplified blade/hub dynamics portion.

Figure 6-8 shows the response of the electrical angle for four excitation configurations. The peak system angle excursion due to the

.5 p.u. wind torque step varies between 0.6 rad for constant PF control to 0.78 rad for constant voltage control at zero droop. By the above criterion then, the PF control is the most effective in minimizing frequency deviation while voltage control with no droop compensation is the least effective. Conversely, as also shown in Figure 6-8, the voltage regulation is the poorest under PF control and the best under voltage (0% droop) control. However, voltage regulator at the effective system bus will be determined by the voltage regulator on the diesel unit, so from the standpoint of steady-state voltage regulation (i.e., 2 or more seconds following the wind torque transient) at the system bus, WTG voltage regulation is of less importance. A characteristics of the var and PF control is that they provide a better damped response by setting the regulator damping gain (GD) to a lower setting. The degree of this improvement is compared in Figure 6-9. In purely voltage control there is little difference between a damping setting of 1. or 0.4 so that one setting is feasible for all three control modes.

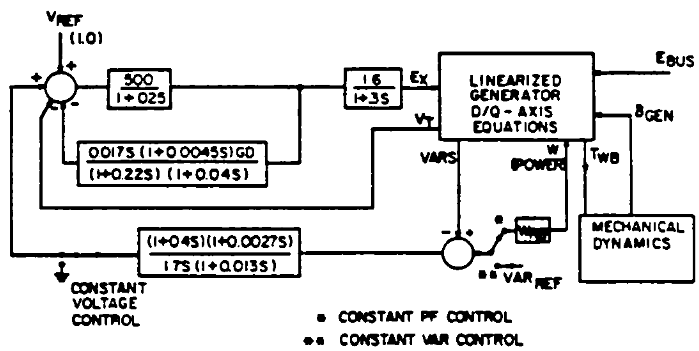


Figure 6-6 Simulation Model for Excitation Systems Evaluation

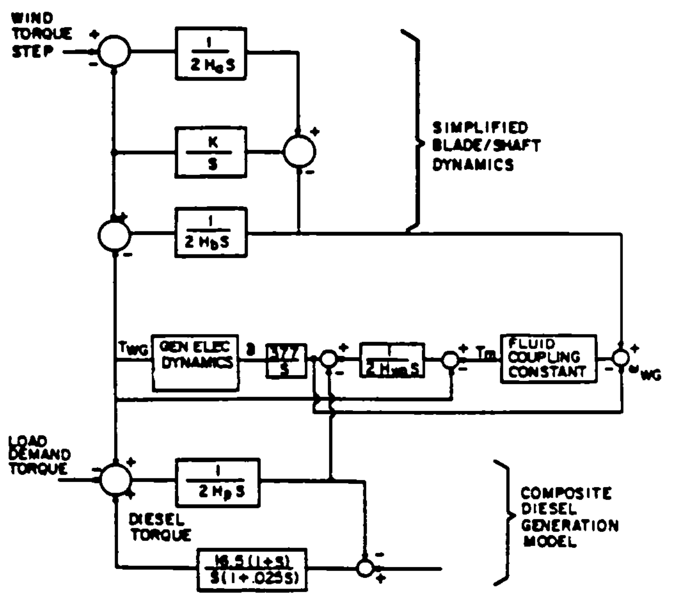


Figure 6-7 Mechanical Portion of Model

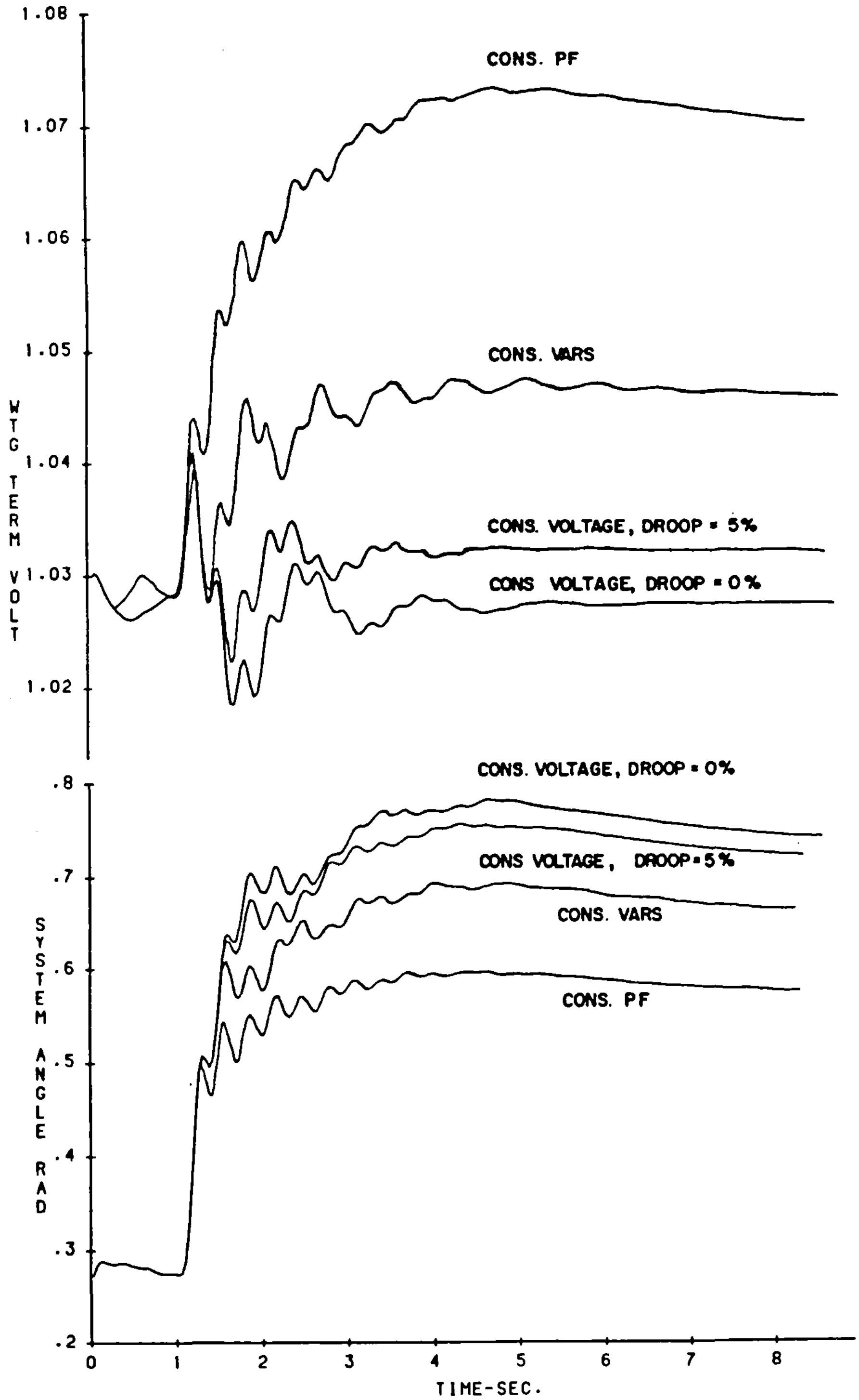


Figure 6-8. Model Responses to Wind Torque Step (Damping Gain, GD=0.4)

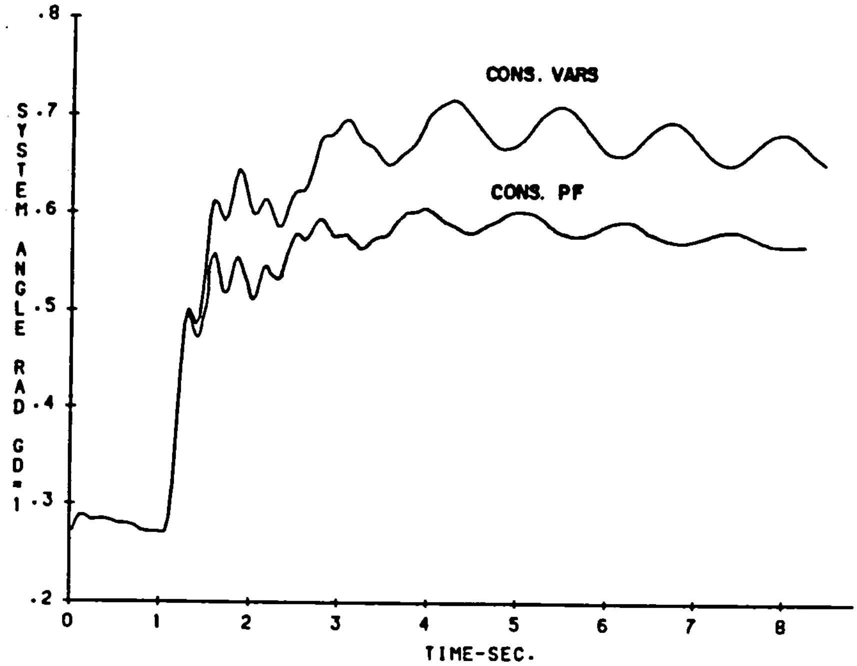


Figure 6-9 Sensitivity of Var and PF Control Response to Damping Loop Gain GD (Damping Gain, GD = 1.0)

Summary

The MOD-OA wind turbine generator operated successfully in all three volt-ampere regulation modes -- constant VAR, constant power factor, and constant voltage. The optimum operating mode for any specific MOD-OA installation is system dependent.

Based on the analysis of the data recordings made on the BIPCO system, comparison among three methods of MOD-OA WTG field excitation (reactive power) control revealed no readily apparent differences in terms of system voltage and frequency (60 Hz) behavior. However, it can be demonstrated by a simulation model that constant power factor control produces a higher transient stability (ability of the WTG to maintain synchronism with the diesel utility) than does either the constant voltage or constant var method.

The low frequency fluctuating reactive power component caused by the combination of MOD-OA WTG, system load and wind dynamics is provided by those generators whose field excitation is under constant voltage control. All generators under fixed excitation or constant power factor control appear to this fluctuating component as an inductive, reactive load, thereby increasing the demand on the voltage controlled generators.

Constant var control has the advantage of providing a non-fluctuating source of reactive power -- a desirable feature when system load is at a low power factor, as was the case during the data collection period on the BIPCO system. At the same time, var control transient stability, while not quite as high as produced by constant power factor control, is higher than that yielded by constant voltage control and is, therefore, a reasonable compromise.

APPENDIX A

Instrumentation Detail

The function of the instrumentation is to measure all electrical and fuel parameters necessary for complete analysis. The instrumentation package was installed January, 1982.

A-1 List of Measurement Quantities

Tables A-1, A-2, and A-3 list the 41 parameters measured by the recording system.

Table A-1

MOD OA 150 kW WTG Measured Quantities

Freq.	Sensor ID	Parameter	Engr. Range	Units	RMU #	MUX
1.0 K	03D100	Blade pitch angle	-90 +10	Deg	3	A
1.5 K	07R302	Alternator rotational speed	0 2250	RPM	3	A
2.0 K	08R354	Nacelle wind speed	0 50	MPH	3	A
2.5 K	08D356	Yaw error	-90 +90	Deg	3	A
3.0 K	02S068	Blade #2 strain shutdown			3	A
3.5 K	01S018	Blade #1 strain shutdown			3	A
4.0 K	09E409	Yaw torque			3	A
4.5 K	14R600	Wind speed 30' met.	0 100	MPH	3	A
5.0 K	11D500	Nacelle direction	0 360	Deg	3	A
5.5 K	12F568	Utility frequency	55 65	Hz	3	A
6.0 K	14R602	Wind speed 100' met.	0 100	MPH	3	A
6.5 K	12V550	Generator voltage ØA	0 360	Volts	3	A
7.0 K	12I556	Generator current ØA	0 400	Amps	3	A
7.5 K	12W564	WTG real power	-300 - +300	KW	3	A
8.0 K	12W566	WTG reactive power	-300 - +300	KVAR	3	A
8.5 K	14R604	Wind speed 150' met.	0 100	MPH	3	A

Table A-2

Diesel #8 Measured Quantities

Freq.	Sensor ID	Parameter	Engr. Range	Units	RMU #	MUX
1.0 K	16M919	#8 fuel mass flowrate	0 - 350	lb/hr	4	A
1.5 K	16W918	#8 reactive power	0 - 100	KVARS	4	A
2.0 K	16D952	#10 throttle displacement	0 - 100	Deg	4	A
2.5 K						
3.0 K	16F901	System frequency	55 - 65	Hz	4	A
3.5 K	16W917	#8 real power	0 - 250	KW	4	A
4.0 K	16I914	#8 current ØA	0 - 75	Amps	4	A
4.5 K	16V911	#8 line voltage AB	2010 - 2790	Volts	4	A
5.0 K	16I921	#8 field current	0 - 100	Amps	4	A
5.5 K	16V920	#8 field voltage	0 - 200	Volts	4	A
6.0 K	16I915	#8 current ØB	0 - 75	Amps	4	A
6.5 K	16V912	#8 line voltage BC	0 - 75	Amps	4	A
7.0 K	16V912	#8 line voltage BC	2010 - 2790	Volts	4	A
7.5 K	16V913	#8 line voltage CA	2010 - 2790	Volts	4	A

Table A-3

Diesel 9 Measured Quantities

Freq.	Sensor ID	Parameter	Engr. Range	Units	RMU #	MUX
1.0 K	16W933	#9 reactive power	0 - 500	KVAR	4	B
1.5 K	16M939	#9 fuel mass flowrate	0 - 350	lb/hr	4	B
2.0 K	16I929	#9 current ØA	0 - 200	Amp	4	B
2.5 K	16D937	#9 throttle displacement	0 - 100	Deg	4	B
3.0 K	16V926	#9 line voltage AB	2010 - 2790	Volts	4	B
3.5 K	16I921	#9 field current	0 - 100	Amps	4	B
4.0 K	16W932	#9 real power	0 - 500	KW	4	B
4.5 K	16V920	#9 field voltage	0 - 200	Volts	4	B
5.0 K	16I930	#9 current ØB	0 - 200	Amps	4	B
5.5 K	16I931	#9 current ØC	0 - 200	Amps	4	B
6.0 K	16V927	#9 line voltage BC	2010 - 2790	Volts	4	B
6.5 K	16V928	#9 line voltage CA	2010 - 2790	Volts	4	B

A-2 Diesel Generator Transducers

Figure A-1 is a one-line diagram indicating the diesel generator measurements under normal operation; only diesel unit #9 and #10 are connected to the power system. Therefore, enclosure B was designed to be switchable to either machine #9 or #10. Enclosure A is always connected to diesel unit #8.

Figures A-2 and A-3 show enclosures A and B layout diagrams respectively. Details of each transducer's wiring are schematically diagrammed in Figures A-4 and A-5.

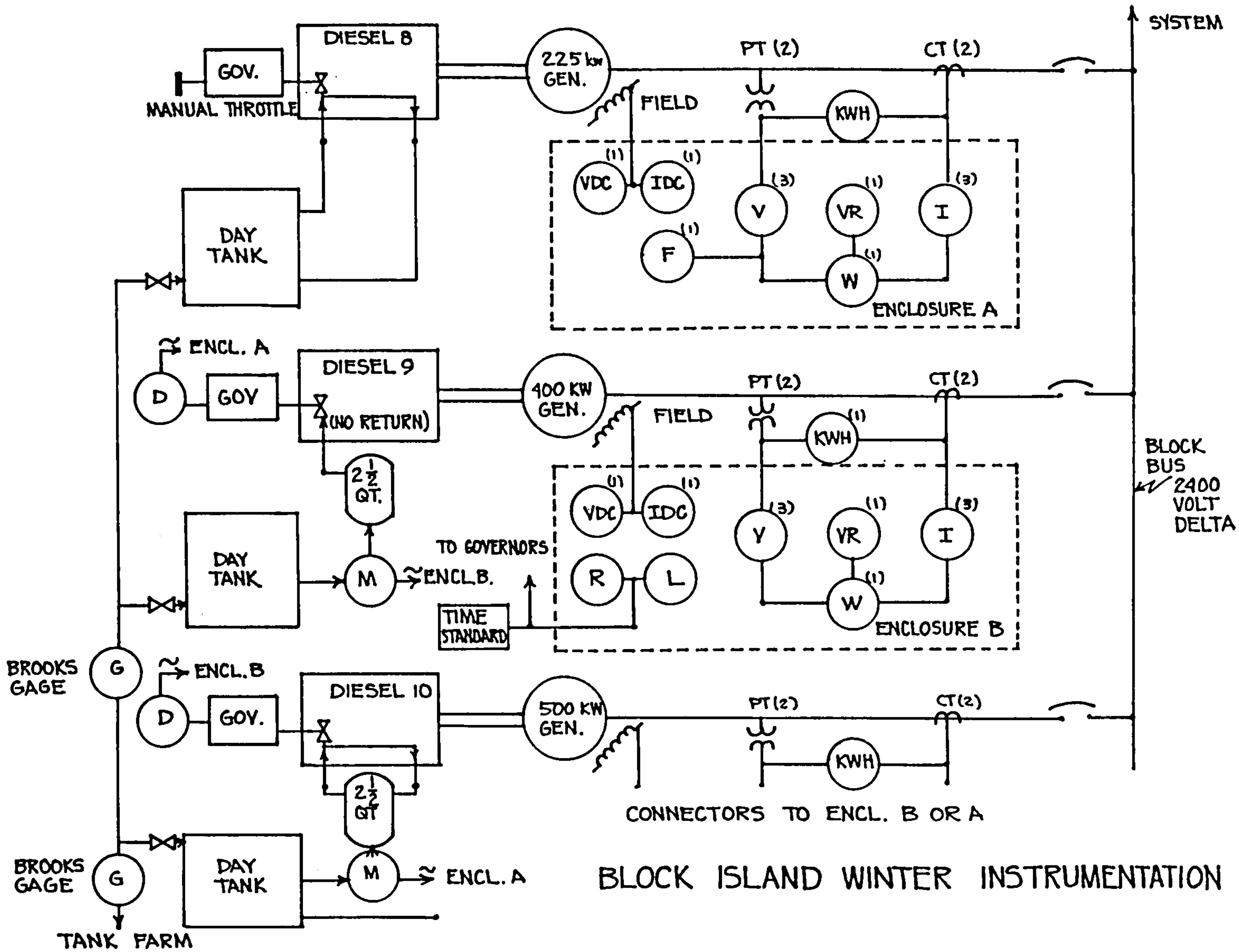


Figure A-1. Block Island Winter Instrumentation

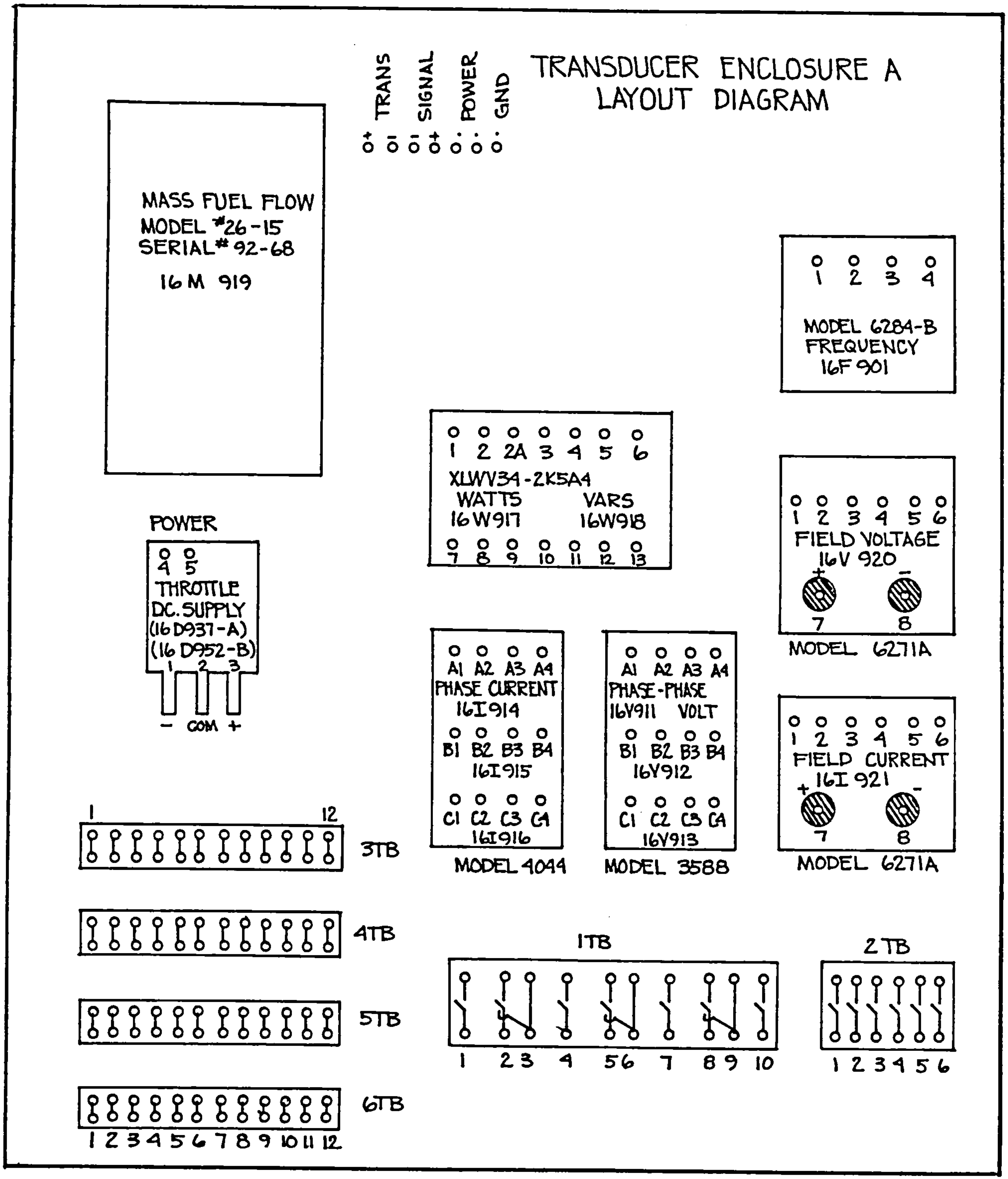


Figure A-2. Transducer Enclosure A Layout Diagram

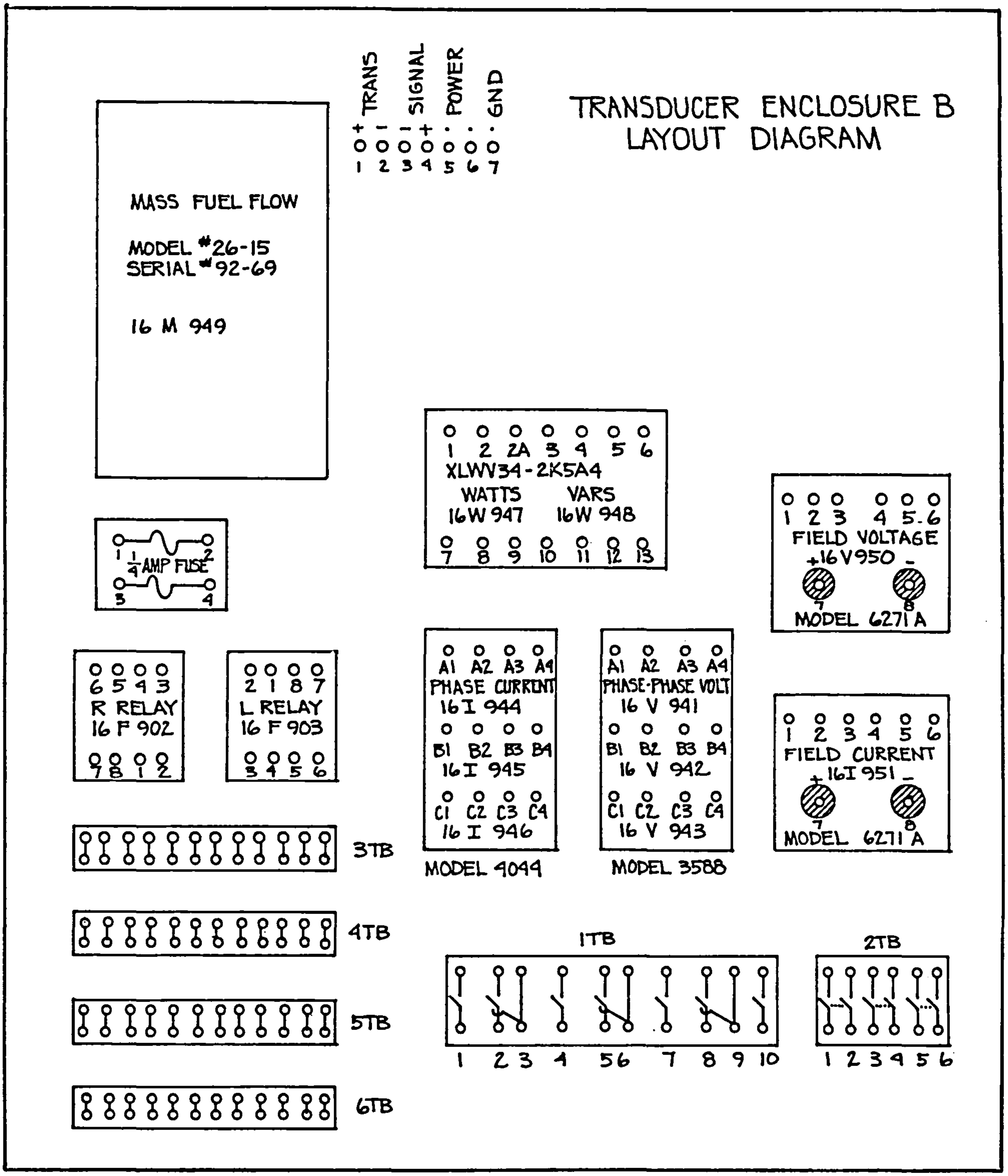


Figure A-3. Transducer Enclosure B Layout Diagram

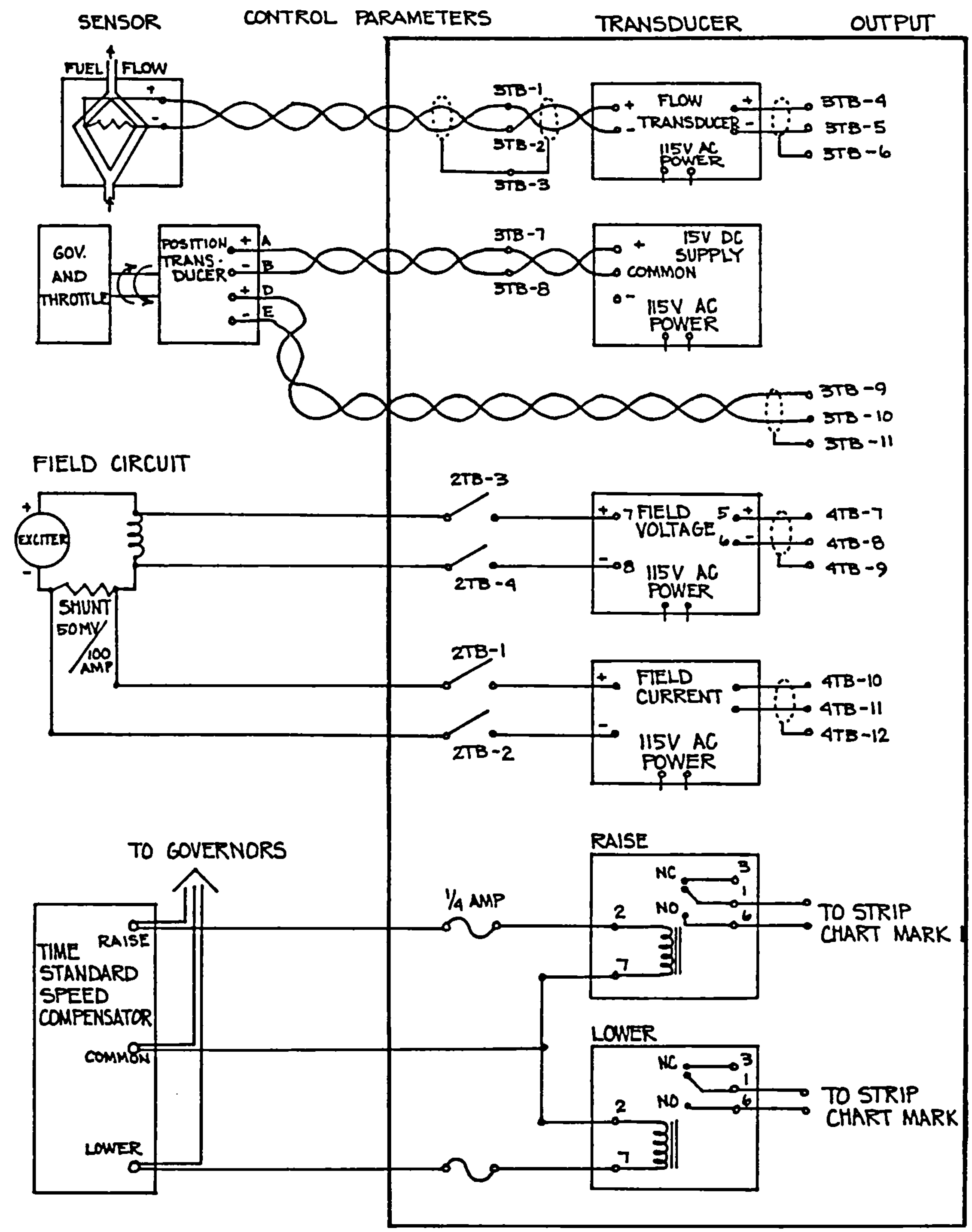


Figure A-4. Transducer Enclosure Connection Diagram

APPENDIX B

Strip Chart Recordings

Figures B-1 through B-14 are selected intervals of the strip chart record. Various levels of system disturbance are visible. The natural diesel system oscillation is visible in Figures B-1, B-12, and B-13. The synchronization transient is visible in Figure B-13. Interaction during fixed pitch operation is presented in Figures B-11, B-13, and B-14. The blade-tower shadow interaction is visible in Figure B-4 to B-9 and B-11. The pitch control operation interaction is visible in Figures B-2 to B-11 and B-14.

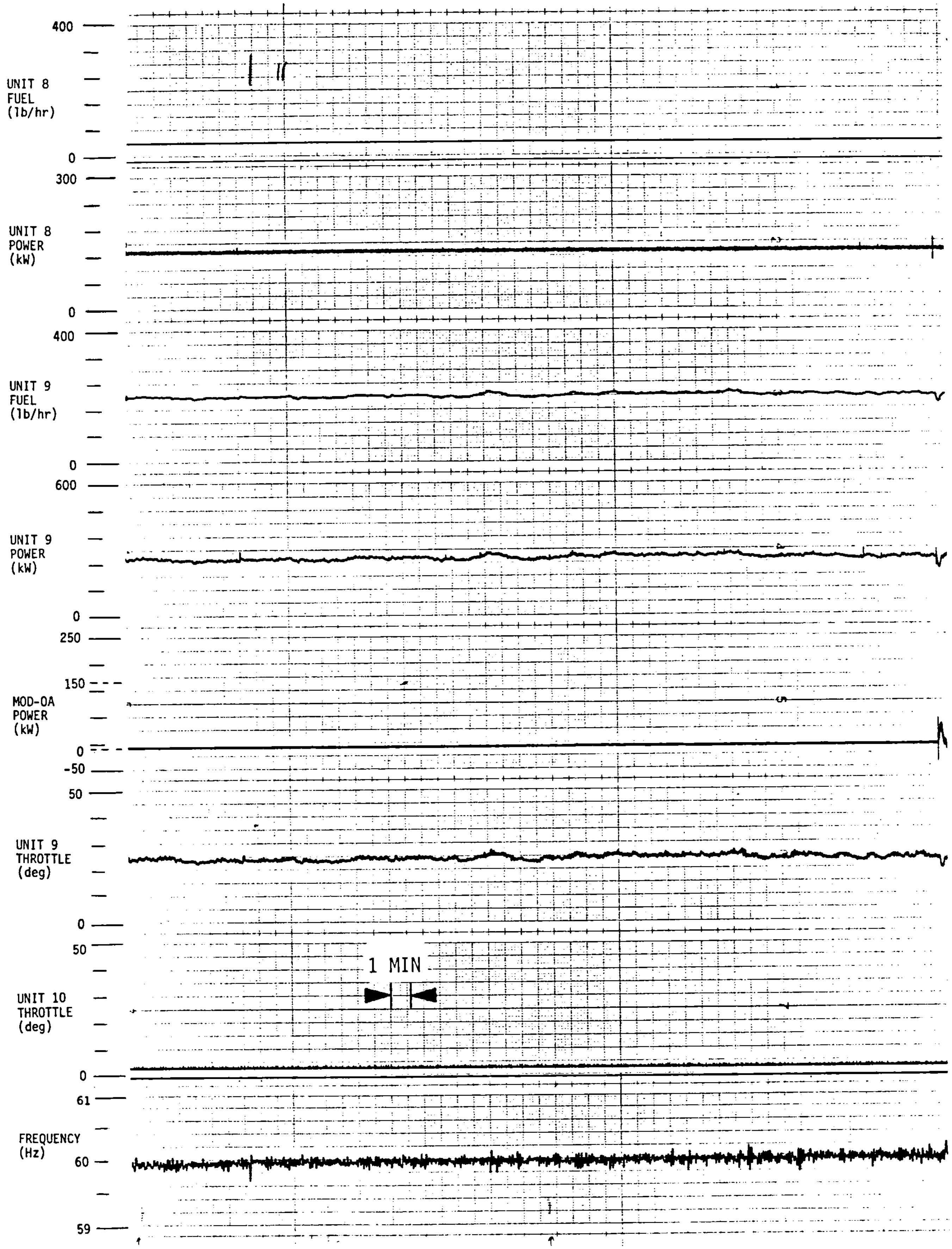


Figure B1 FS3F2 MOD-OA OFF
Natural Oscillation of System Apparent

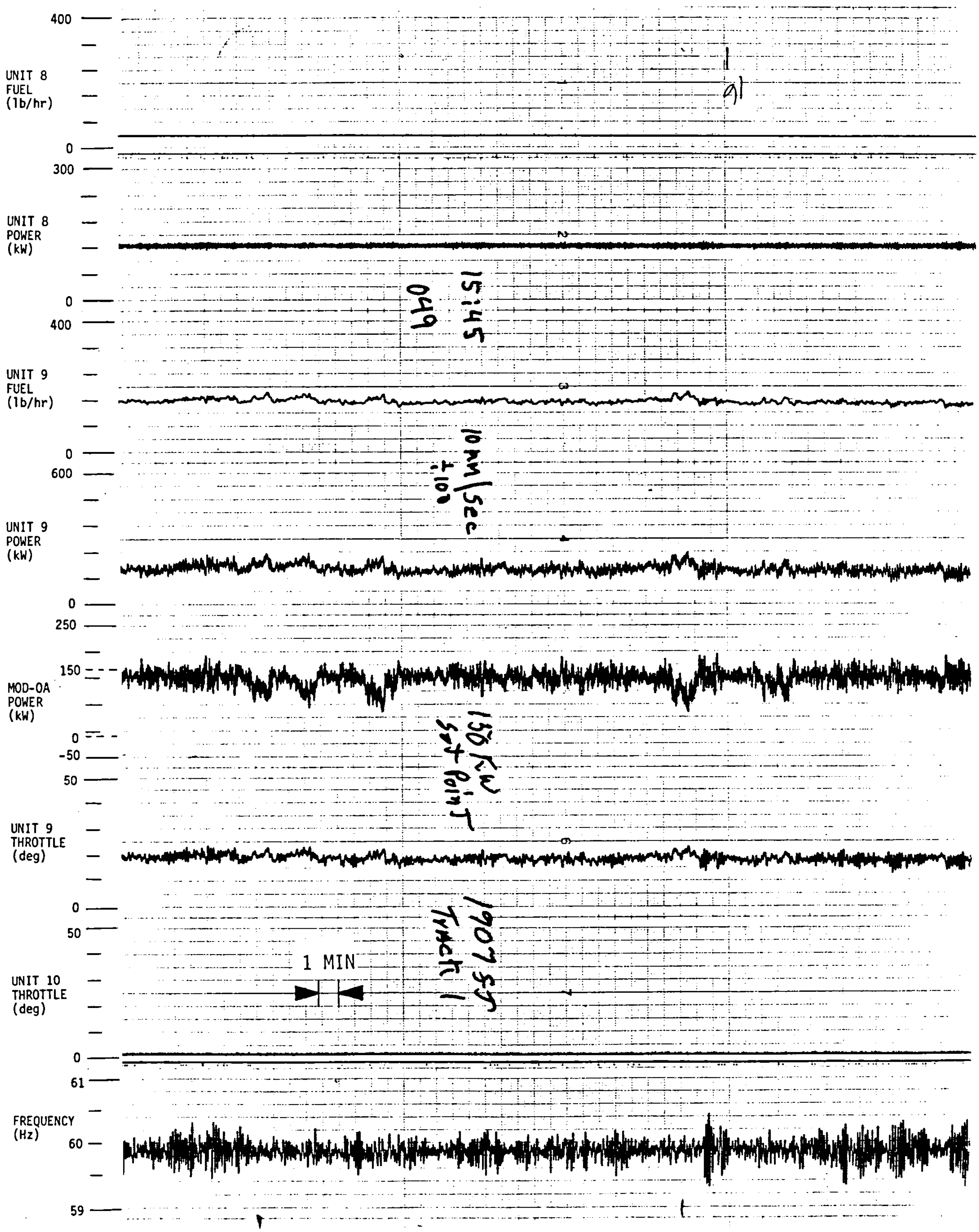


Figure B2 FS4F2 MOD-OA Controlling for 150 kW. Intermittent Pitch Control Results in Intermittent Oscillations

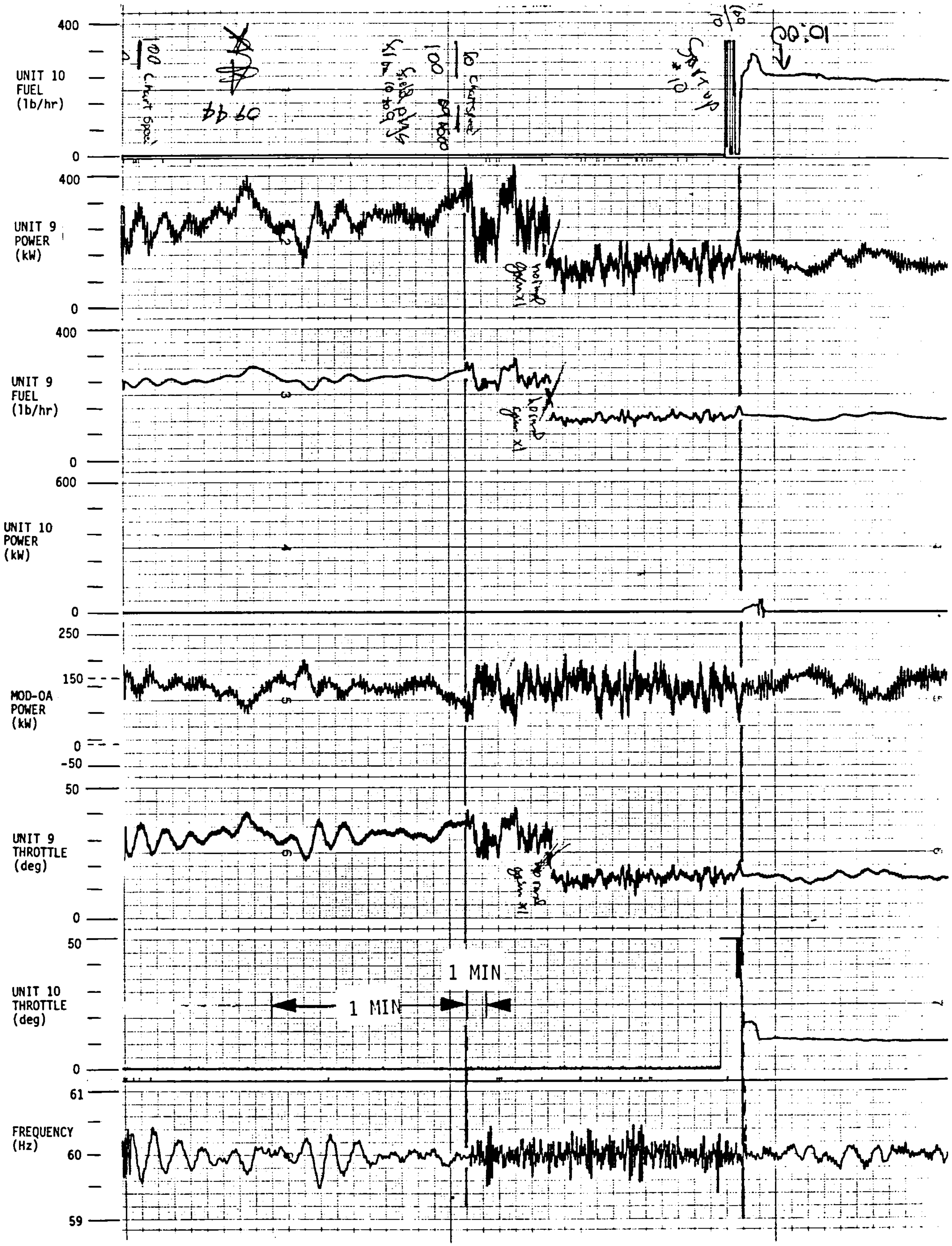


Figure B3 FS2F1 0-1300 Sec. MOD-OA Controlling for 150 kW Intermittent Pitch Control

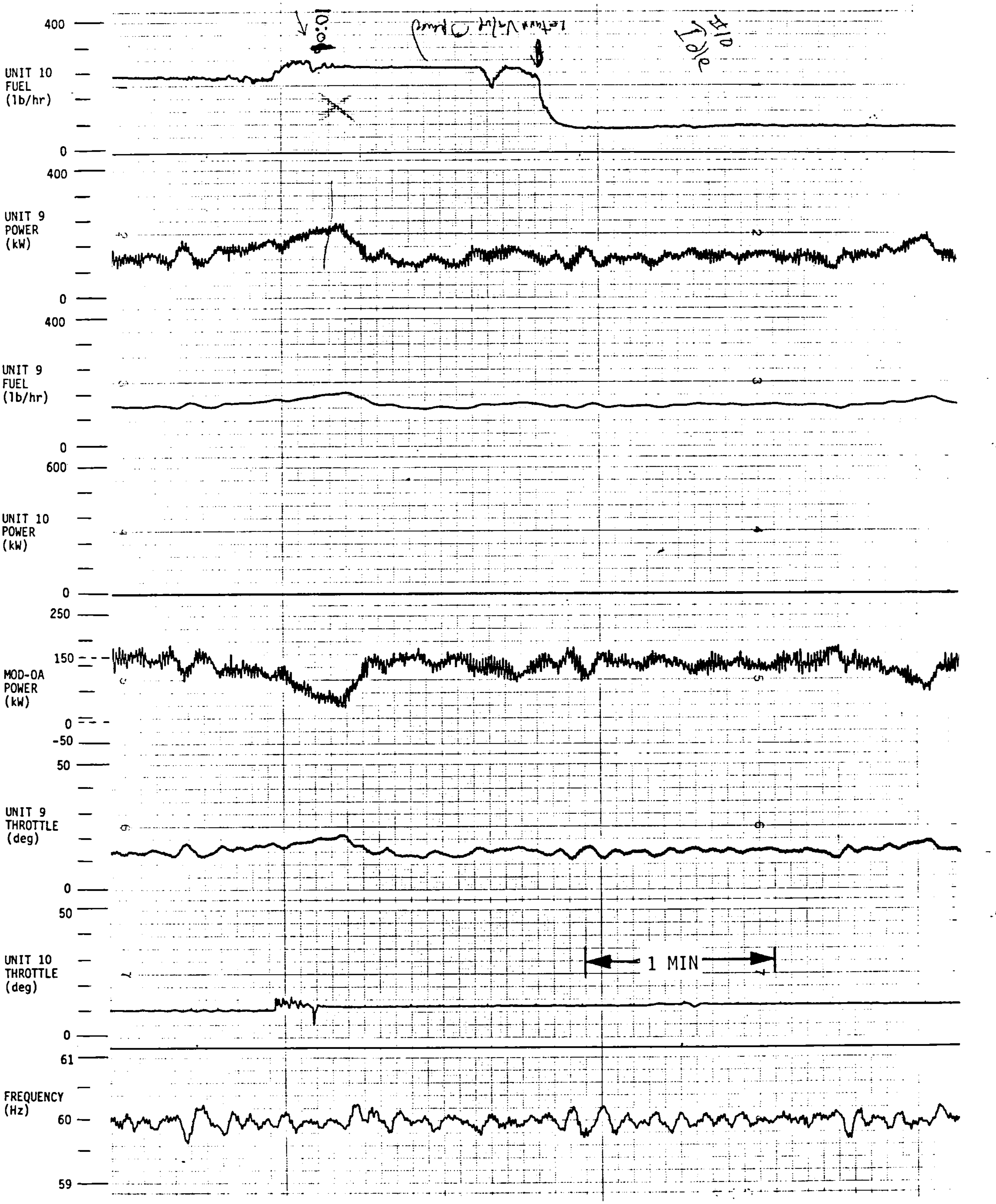


Figure B4 FS2F1 1350-1575 Sec. MOD-OA Controlling for 150 kW

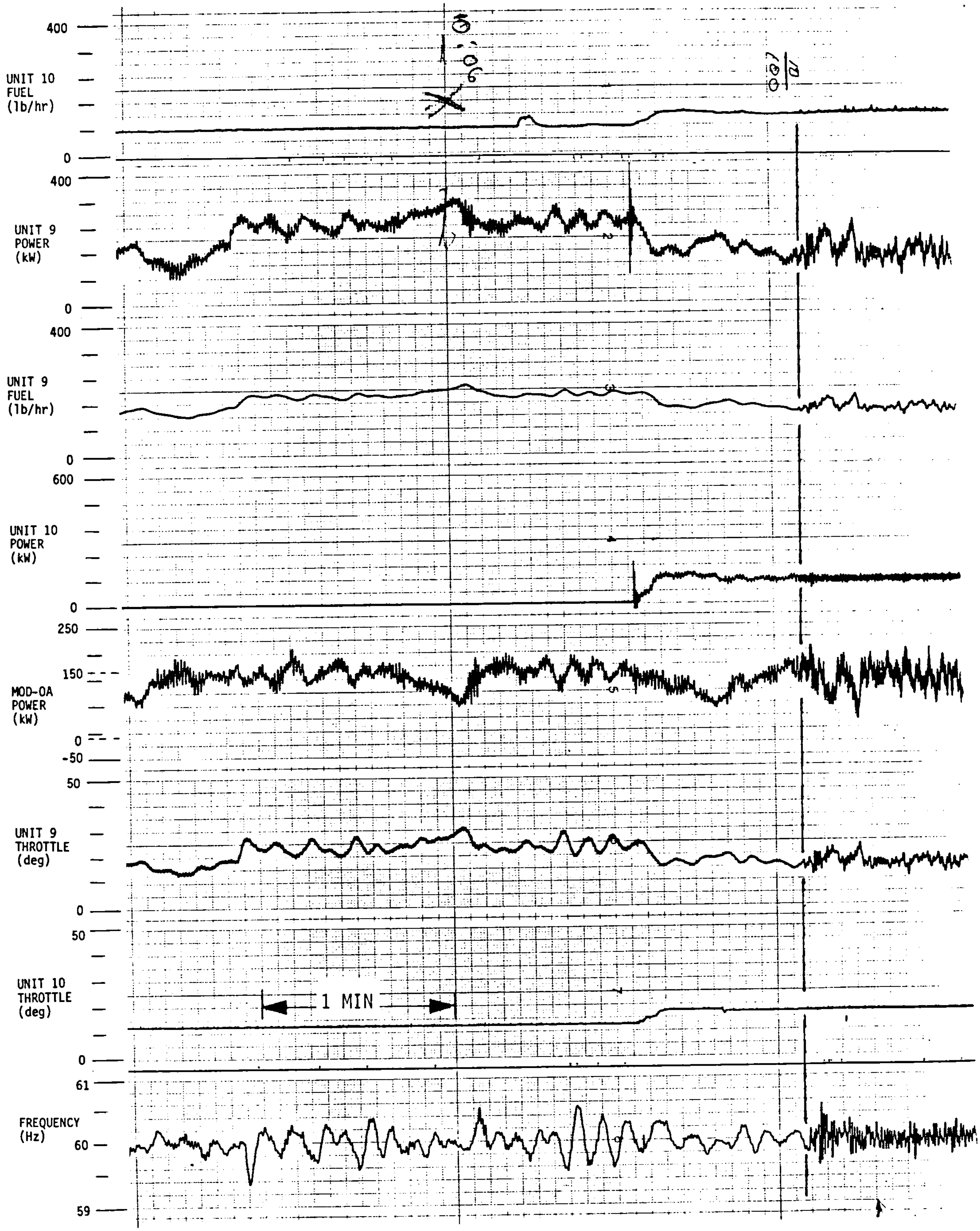


Figure B5 FS2F1 1575-1800 Sec. MOD-OA Controlling for 150 kW
Unit #10 Comes on Line - Oscillations Still Present

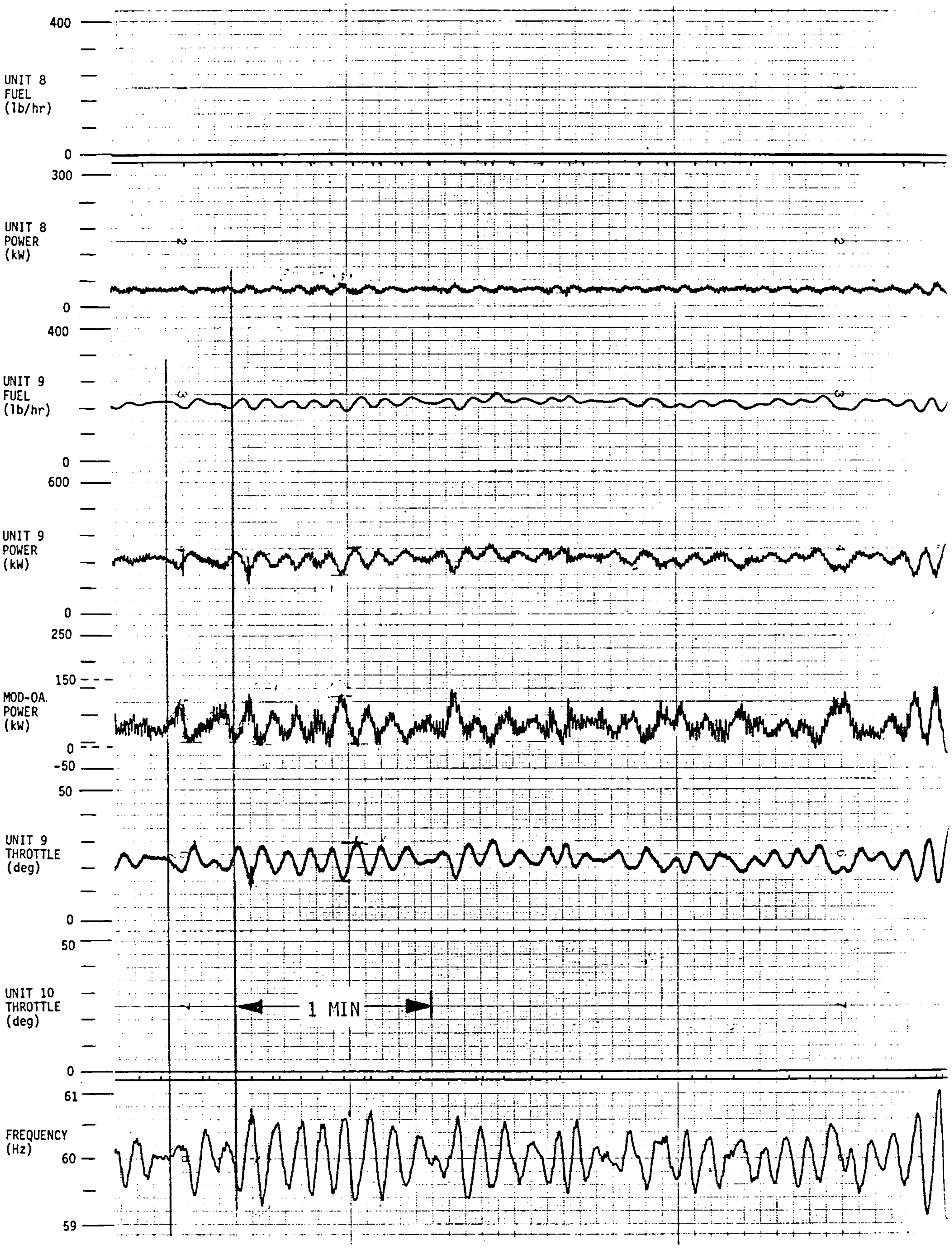


Figure B6 FS2F2 0-250 Sec. MOD-0A Controlling for 50 kW
Amplitude of Frequency Oscillations Reach 2 Hz

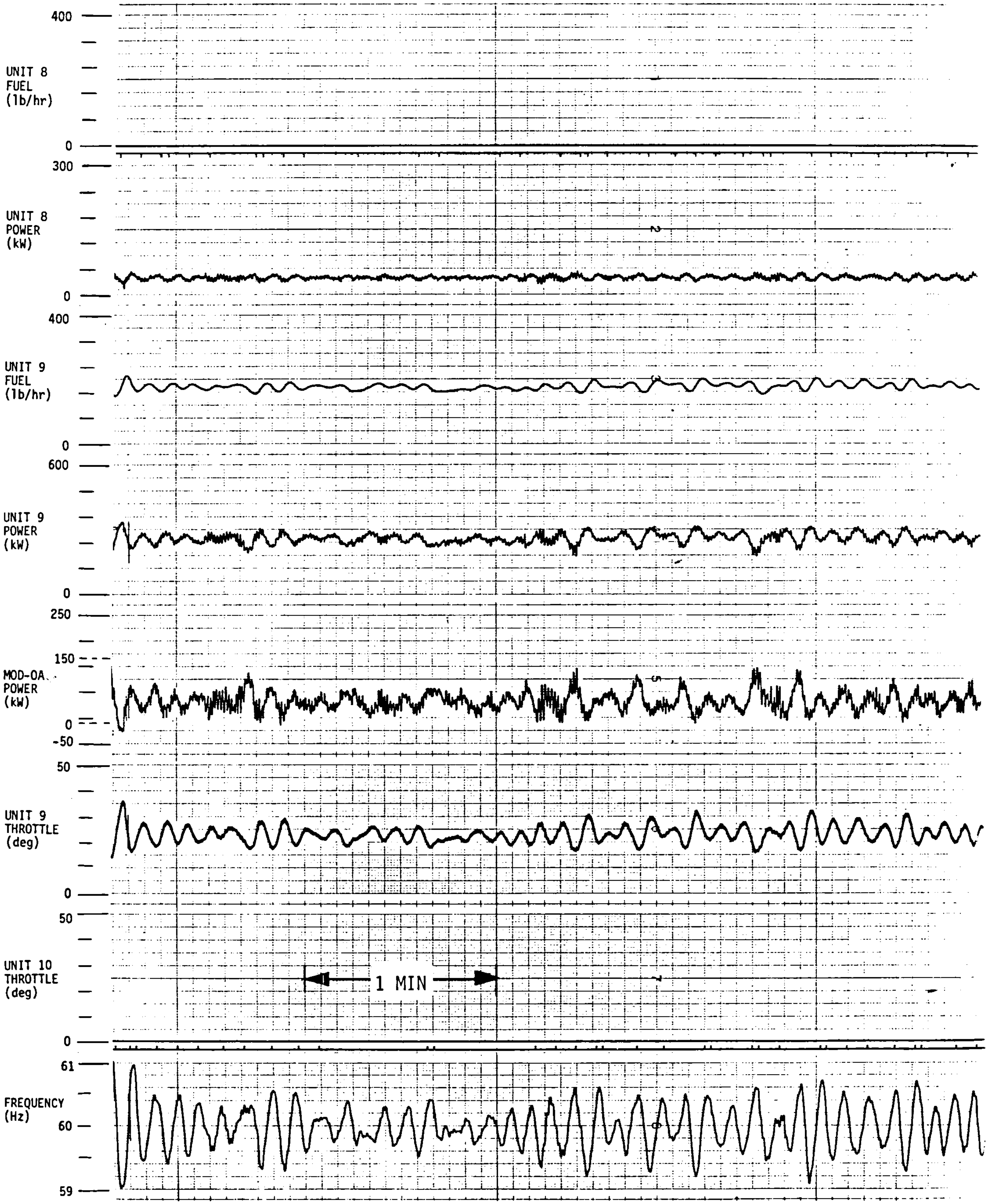


Figure B7 FS2F2 250-500 Sec. MOD-OA Controlling for 50 kW, One Second Oscillation Apparent in WTG Power Corresponding to Rotor Speed

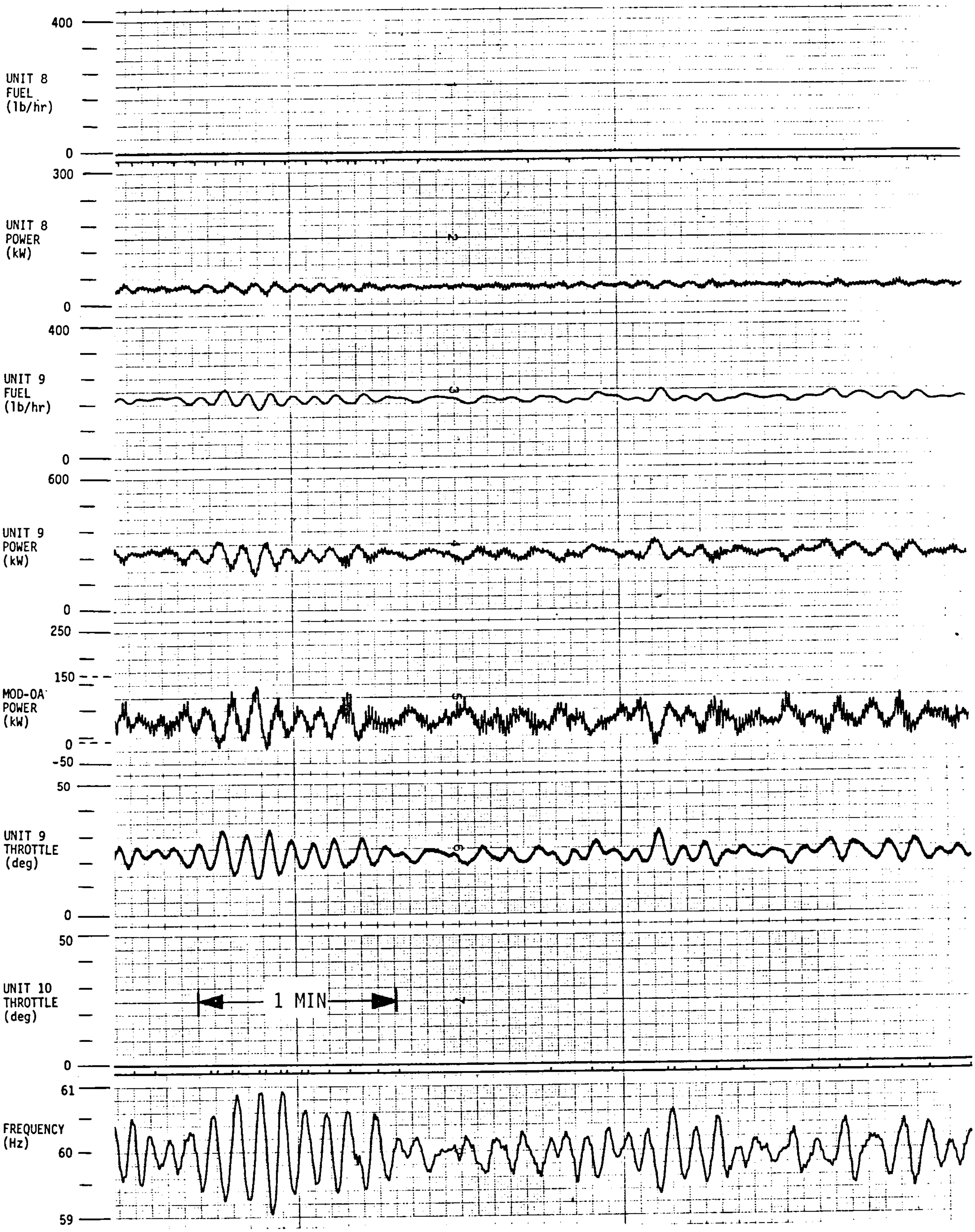


Figure B8 FS2F2 500-750 Sec. MOD-OA Controlling for 50 kW

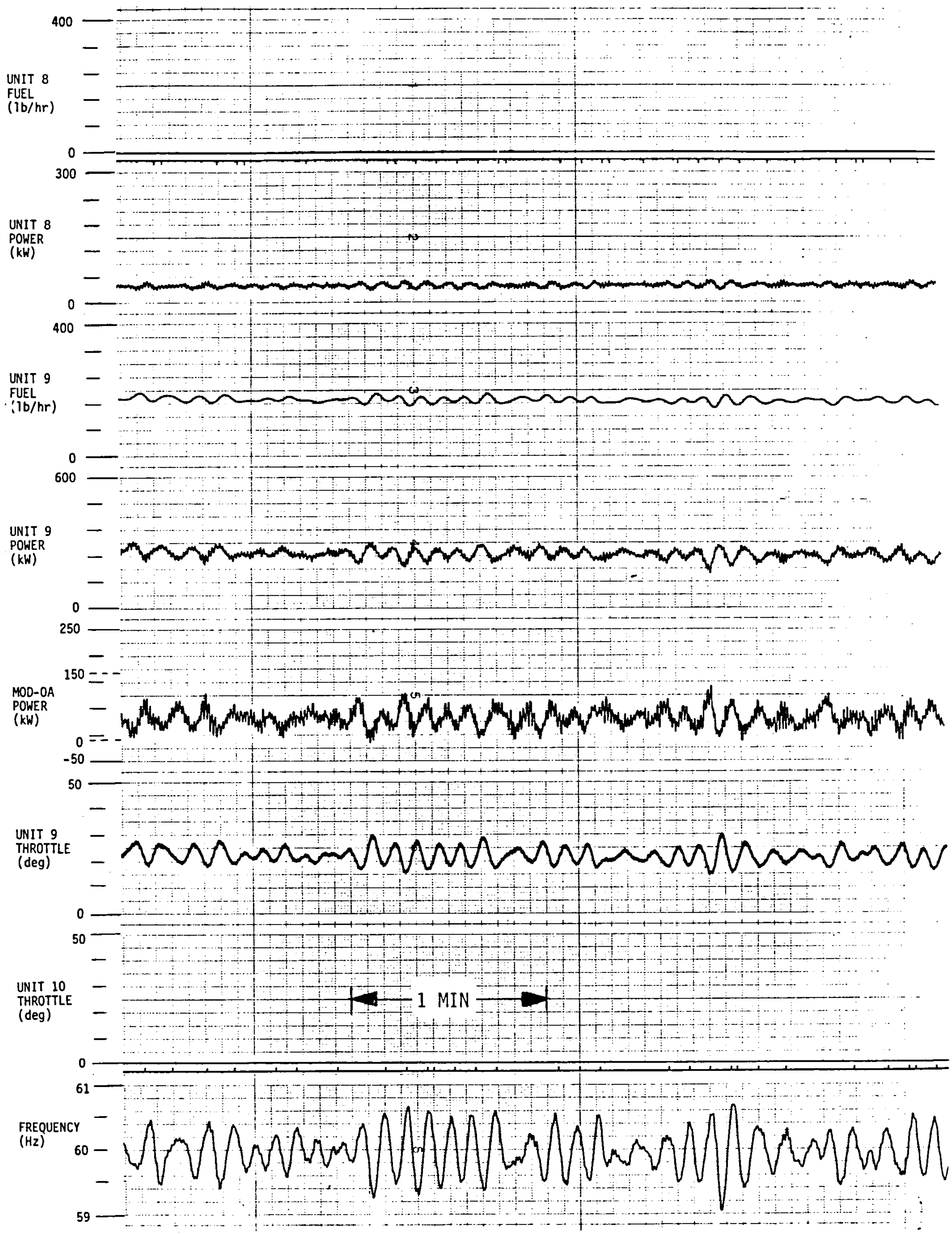


Figure B9 FS2F2 750-900 Sec. MOD-OA Controlling for 50 kW

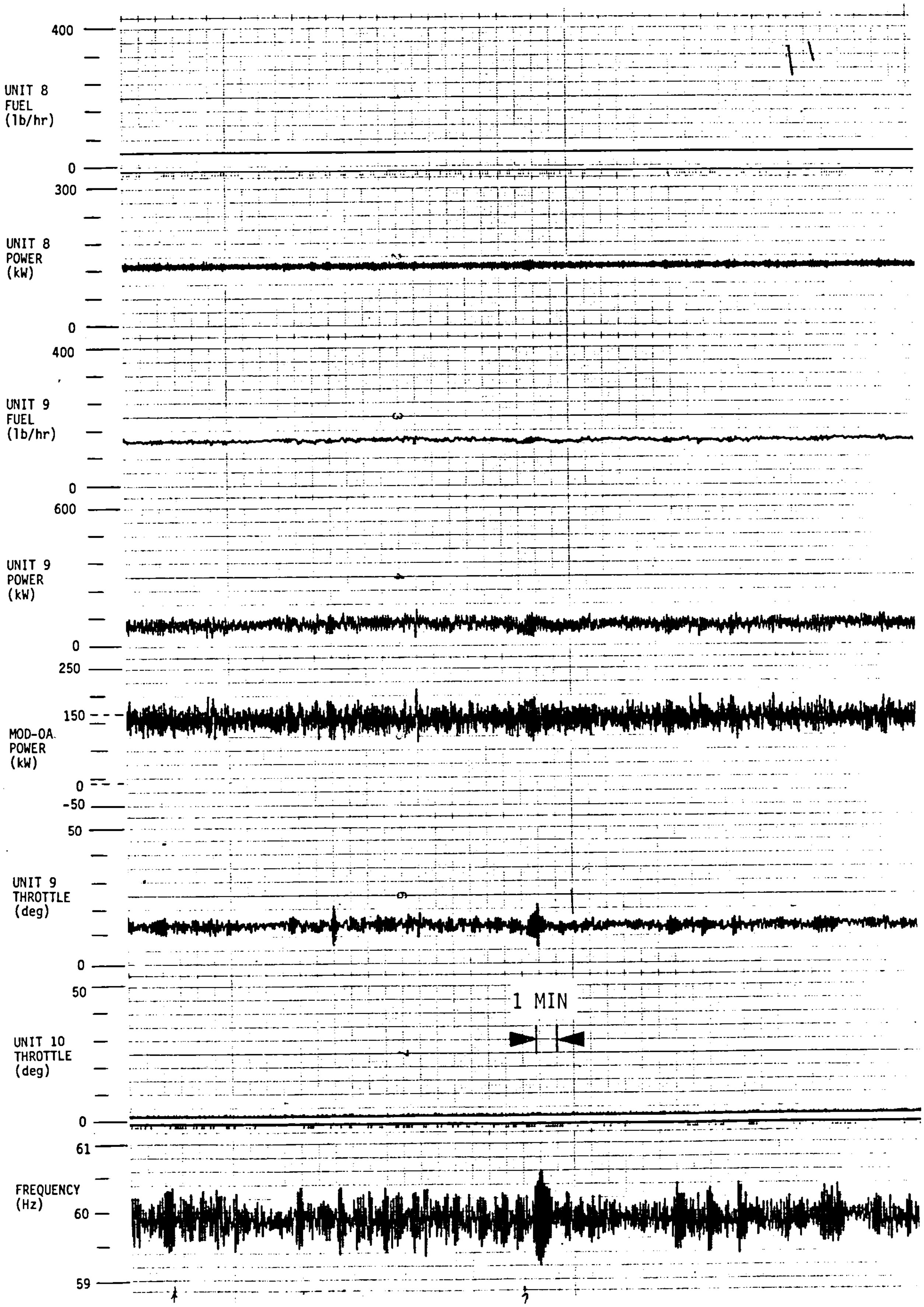


Figure B10 FS3F6 MOD-OA Controlling for 150 kW
Continuous Oscillation Apparent

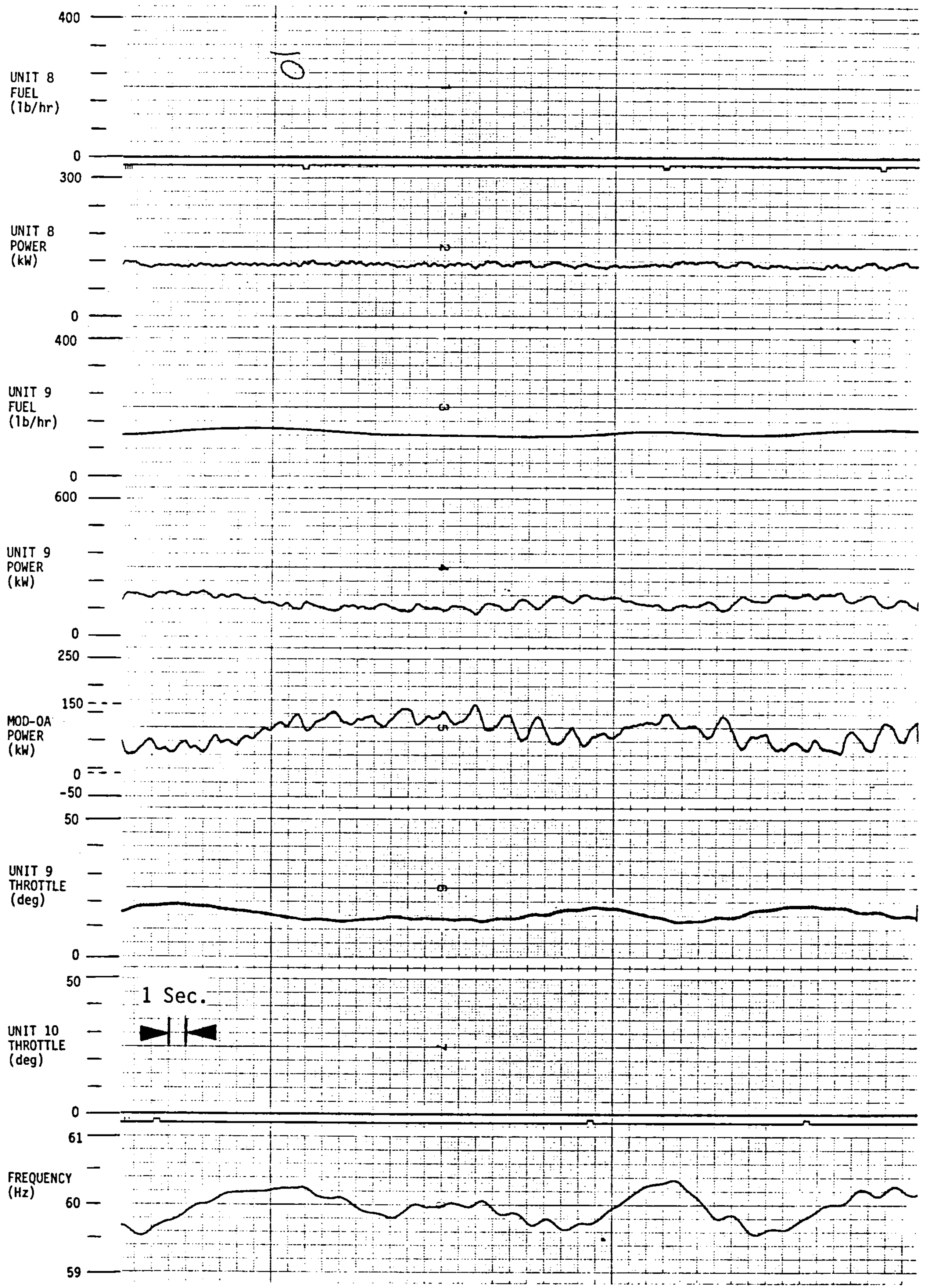


Figure B11 February 3, 16:00, 10 mm/Sec. Chart Speed
Showing One Second Power Swings in MOD-OA

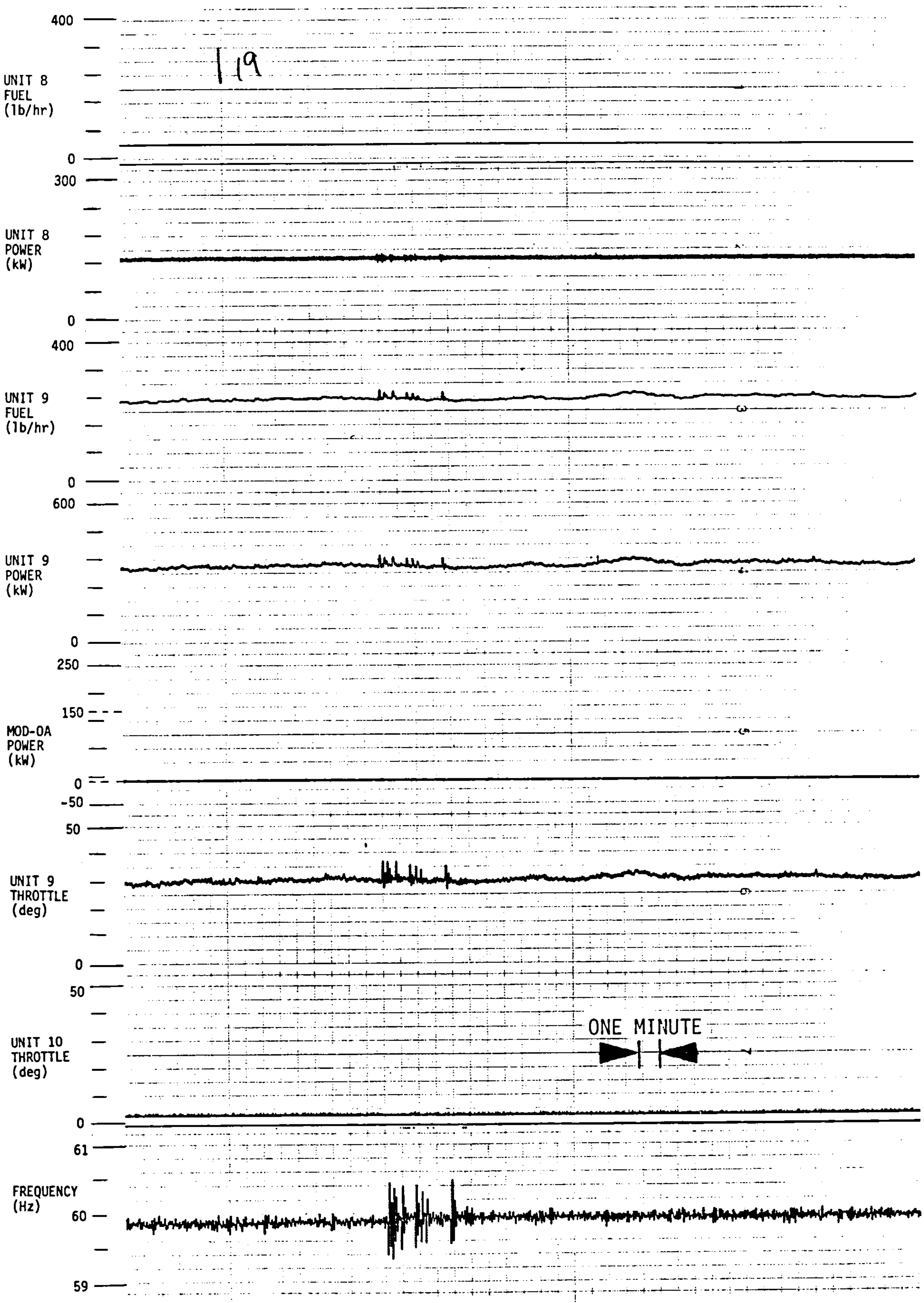


Figure B-12. February 15, 1982 - 6:00 p.m.
Diesel Governor Interaction During Load Fluctuations

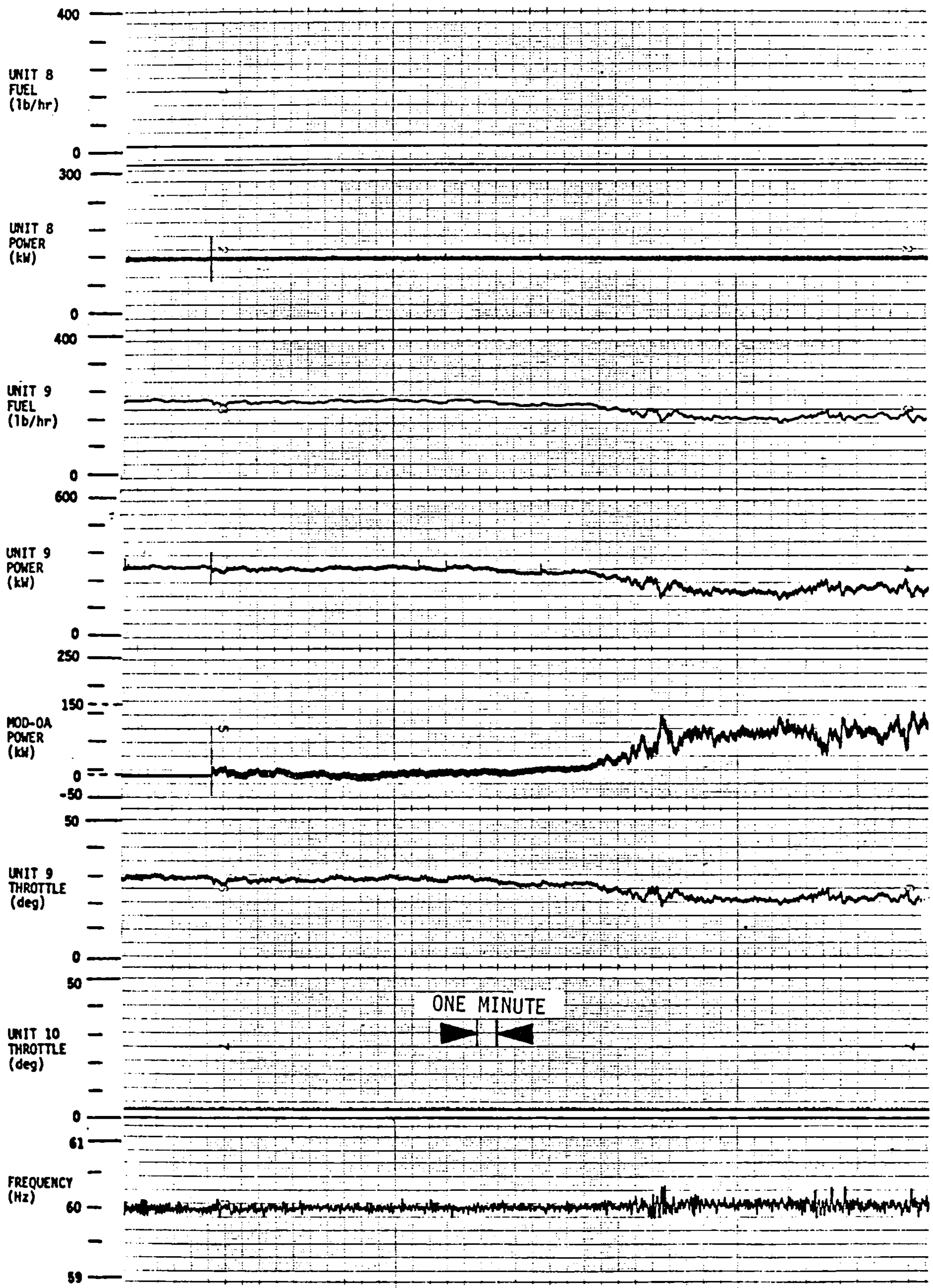


Figure B-13. February 16, 1982
MOD-OA Synchronization and Fixed Pitch Operation

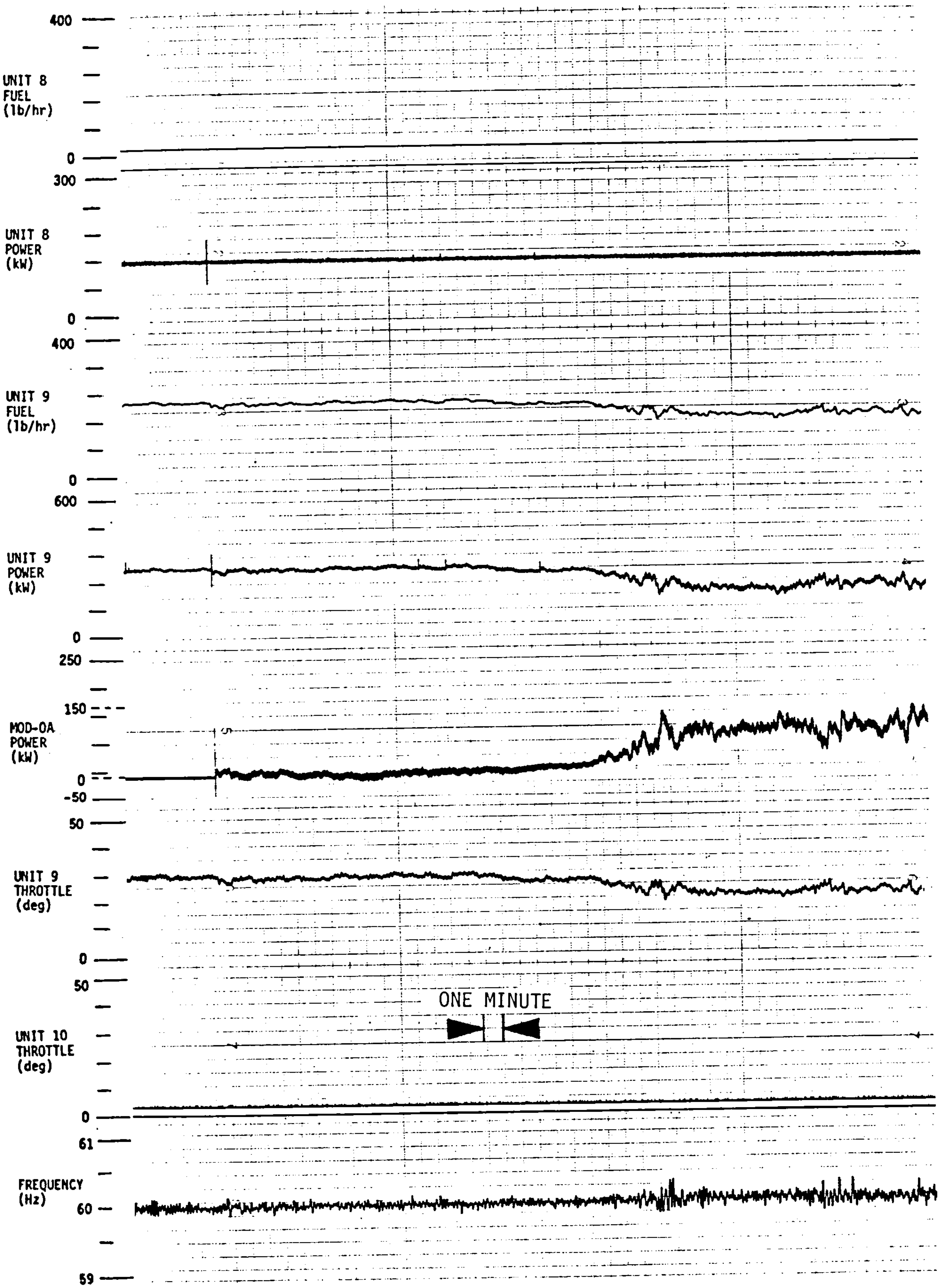


Figure B-13. February 16, 1982
MOD-OA Synchronization and Fixed Pitch Operation

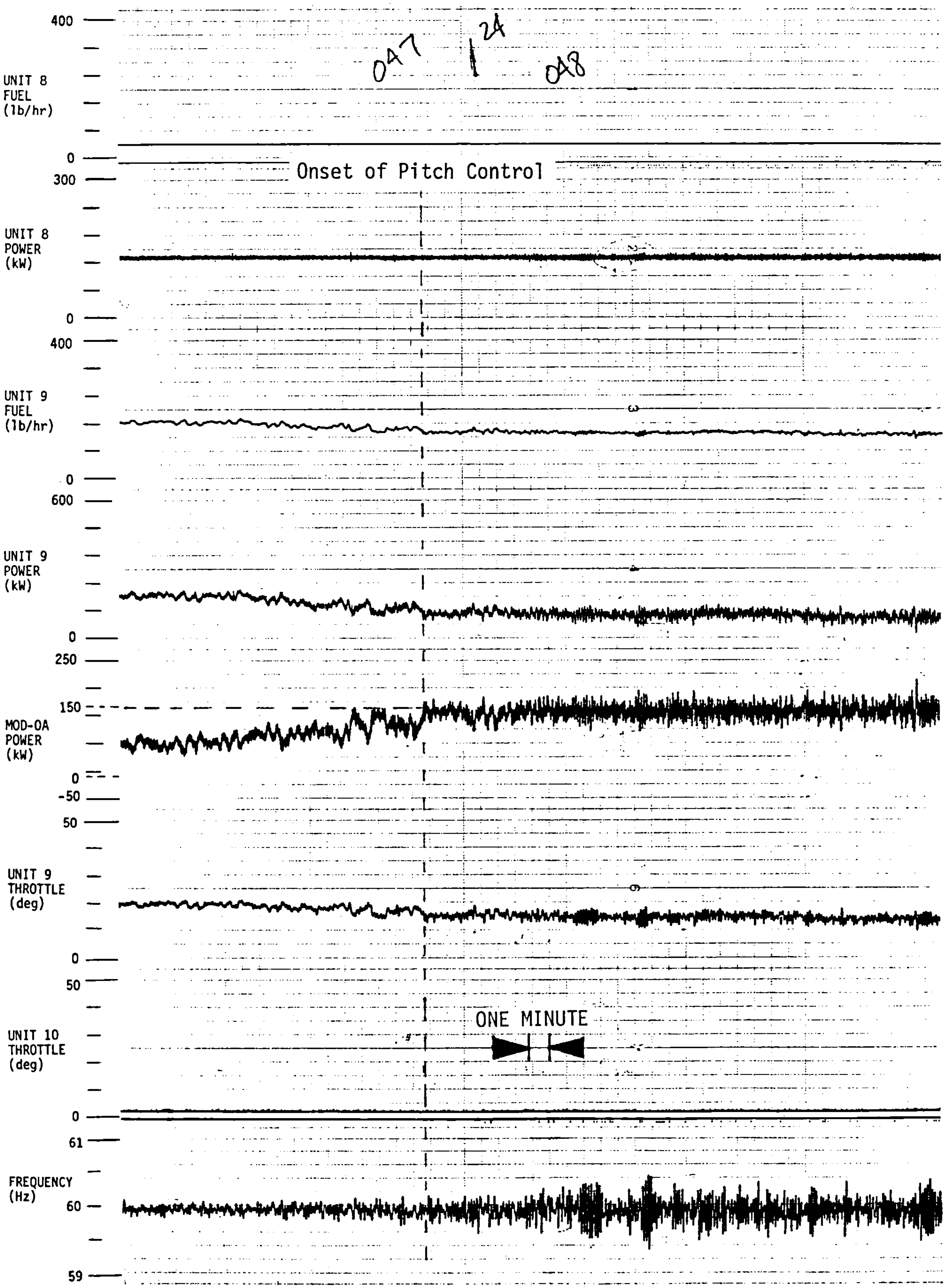


Figure B-14. February 16, 1982 - Midnight
MOD-OA Fixed Pitch and Pitch Control

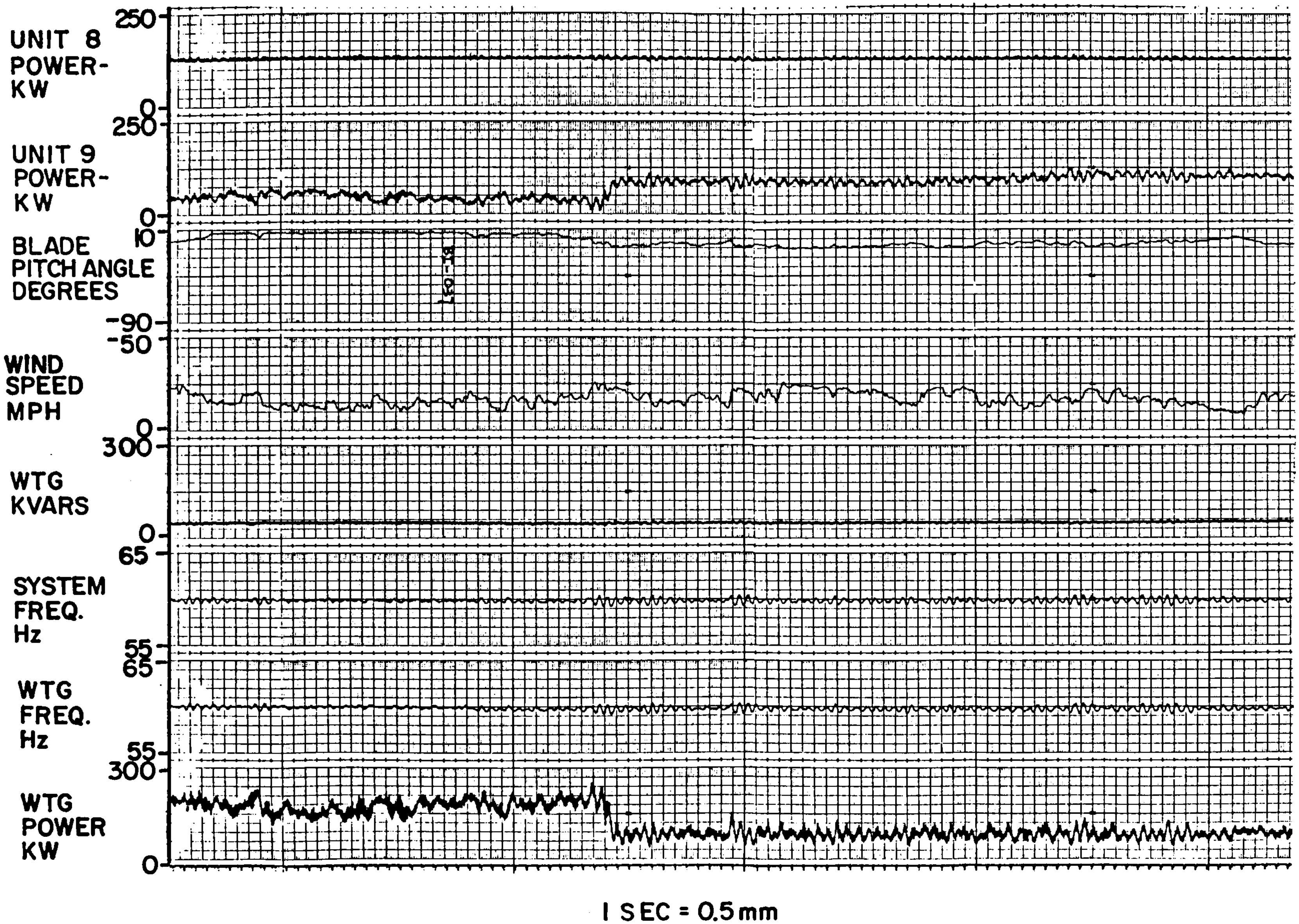


Figure B-15. Power Setpoint Change 150 kW to 50 kW
Julian Time: 37:16:35

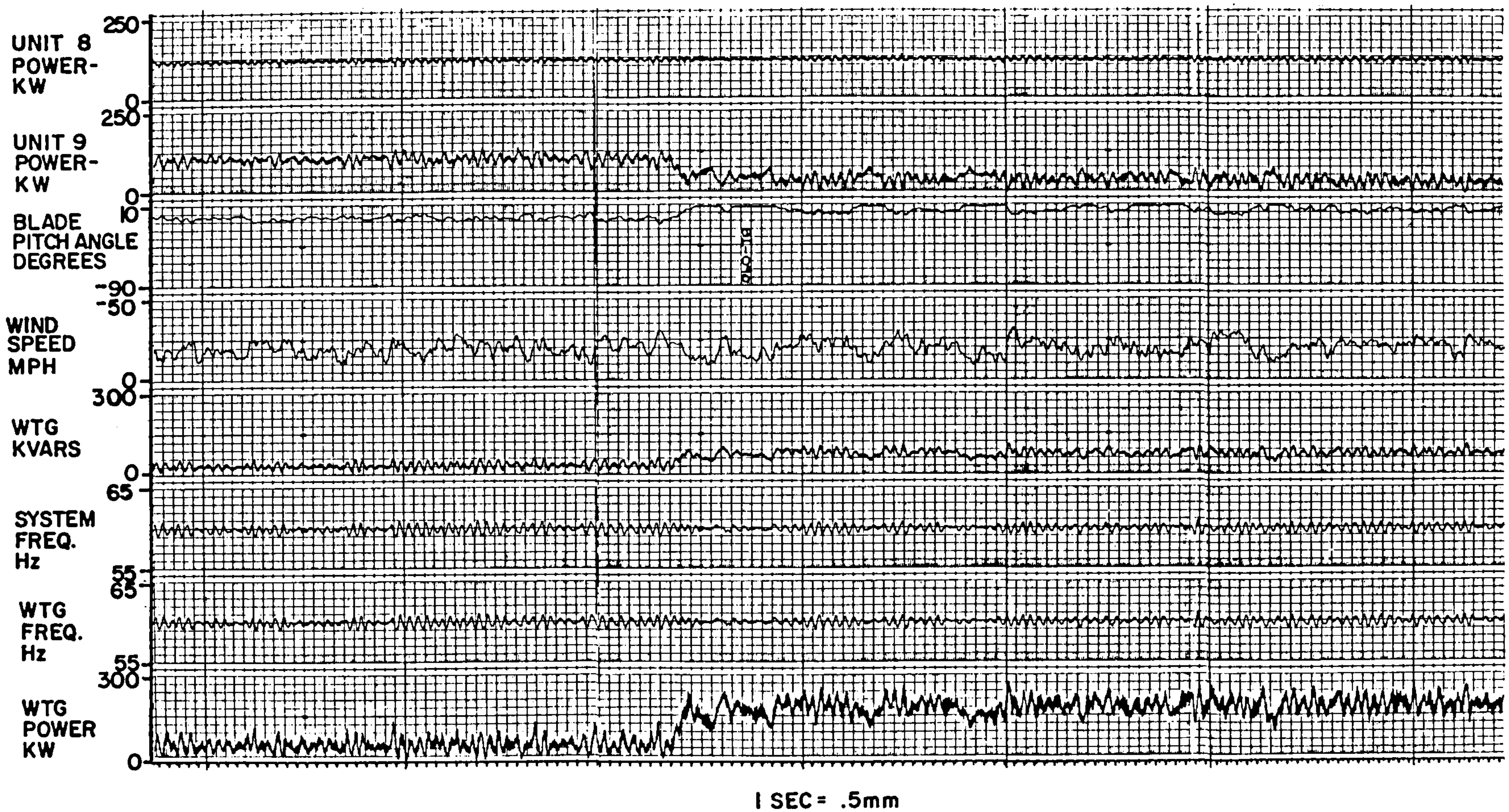


Figure B-16. Power Setpoint Change 15 kW to 150 kW
Julian Time: 90:09:30

APPENDIX C

Tables C1 to C3

Digitized Time Files	Date	Start	Stop	Sample Rate (Sec.)
FS1F1	Feb 1	14:39	14:54	0.50
FS1F2	Feb 2	16:59	17:10	0.50
FS1F3	Feb 3	13:23	13:35	0.50
FS2F1	Feb 3	9:40	10:10	0.23
FS2F2	Feb 3	14:35	14:51	0.50
FS2F3	Feb 3	15:40	15:50	0.50
FS2F4	Feb 3	15:00	15:10	0.50
FS3F1	Feb 18	23:55	00:15	0.50
FS3F2	Feb 16	10:55	11:15	0.50
FS3F3	Mar 15	9:07	9:20	0.51
FS3F4	Mar 15	11:14	11:35	0.51
FS3F5	Mar 15	18:10	19:10	0.51
FS3F6	Feb 17	00:34	00:50	0.51
FS4F1	Feb 17	18:55	19:15	0.51
FS4F2	Feb 18	15:35	15:55	0.51
FS10F1	May 19	14:00	14:25	0.10
FS12F1	May 19	16:00	16:34	0.10

Digitized Time Files Containing 40 Data Channels Each

Table C1. Selected Time Intervals for Digital Analysis

Table C-2. Inertia Constants of Rotating Machines

	J (lb-ft^2)*	RPM	KVA	H(KWS/KVA)	H(on 250 KVA Base)
Diesel #8	932	1200	281	1.10	1.24
Diesel #9	4510	1200	500	3.0	6.0
Diesel #10	5260	1200	625	2.8	7.0
MOD-0A					
Blades, hub, gears	3.78×10^6	31.5			
Brake, ½ fluid coup.	29.7	1400			
Subtotal			250	3.52	3.52
½ Fluid coup, shaft	21.0	1400			
Pulley, ½ belts	23.1	1400			
Pulley, ½ belts	16.1	1800			
Generator rotor	45.3	1800			
Subtotal			250	0.26	0.26

$$H = 231 \times 10^{-9} \quad J\ rpm^2/KVA$$

From Ref. 23

Table C-3. WTG Alternator Electrical Constant

Rating: 250 kVA, 480 V, 60 Hz, .8 PF

Configuration: 4 wire, grounded wye, 4 poles, 1800 rev/min.

Following direct and quadrature axis reactanes in per unit on machine rating:

X_d - 1.807	X_q - 1.07
X'_d - .284	X'_q - 1.069*
X''_d - .128	X''_q - .094*
X_l - .0673	r_a - .012
T'_{do} - 2.605*	T'_{qo} - .11*
T''_{do} - .025*	T''_{qo} - .021*

* Data not provided by manufacturer - values assumed yield system damping close to that observed on measurements.

APPENDIX D

Nacelle Wind Speed Measurements for Figures D5-3 to D6-3

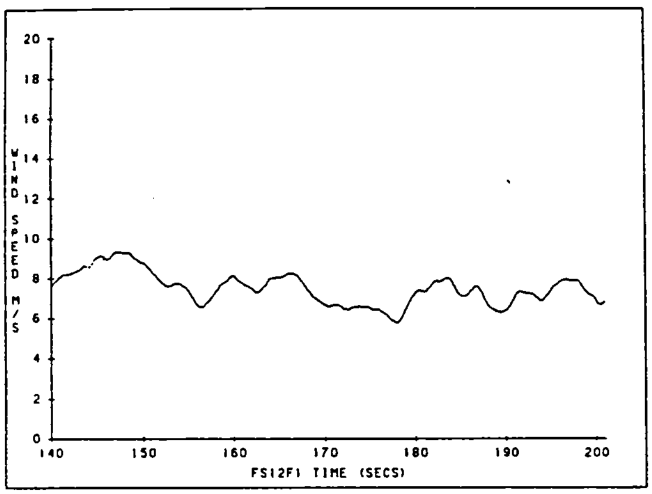


Figure D5-3

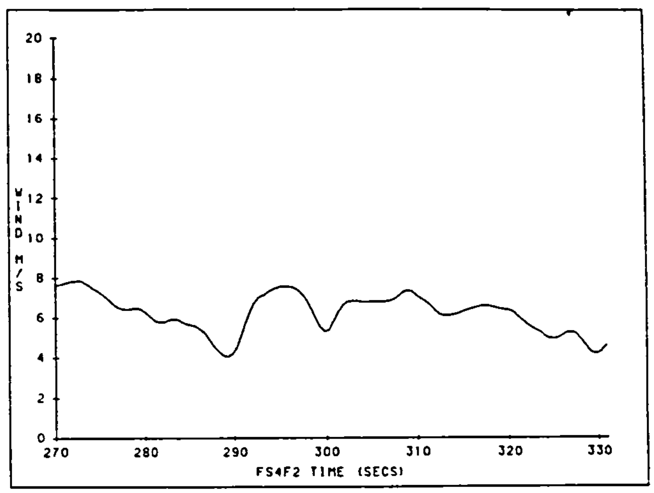


Figure D5-5

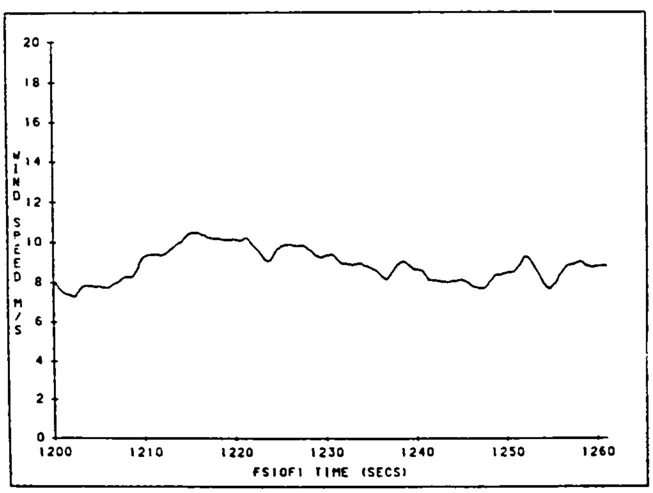
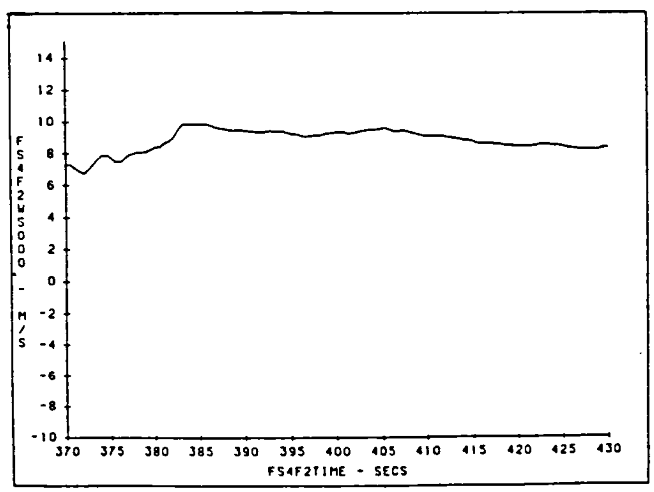


Figure D5-4



Nacelle Wind Speeds

Figure D5-6

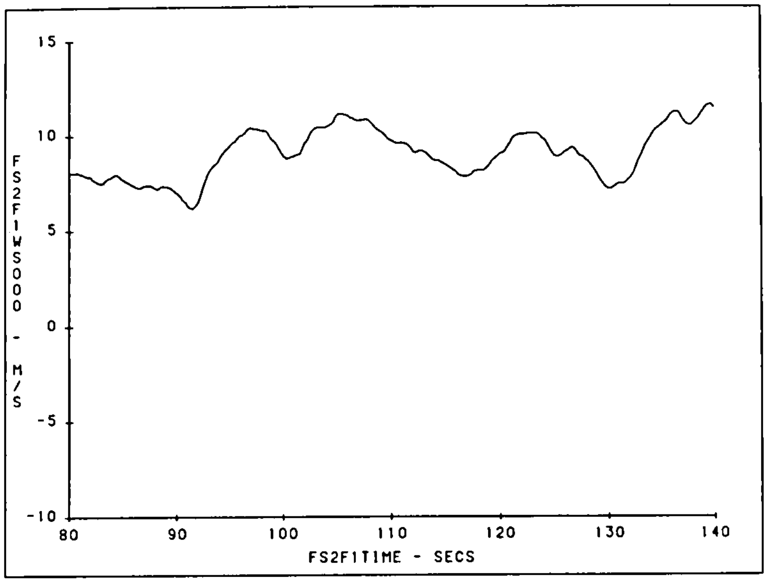


Figure D5-7

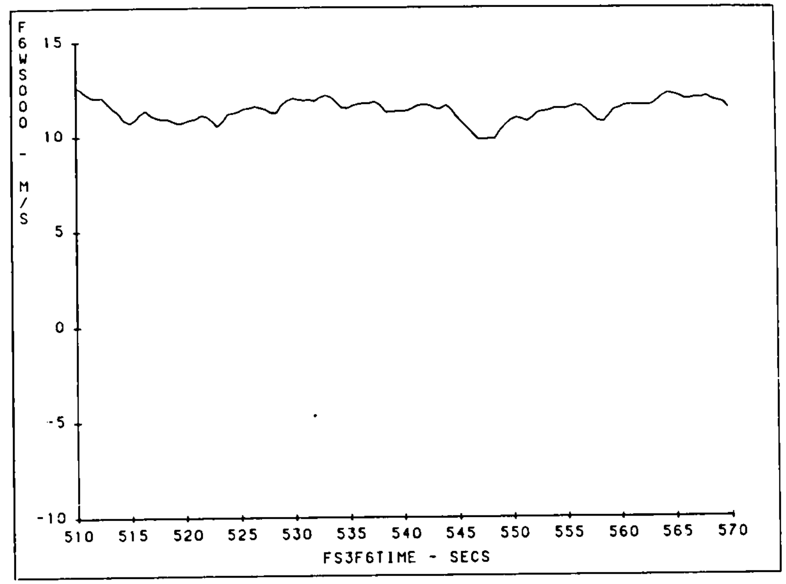


Figure D5-9

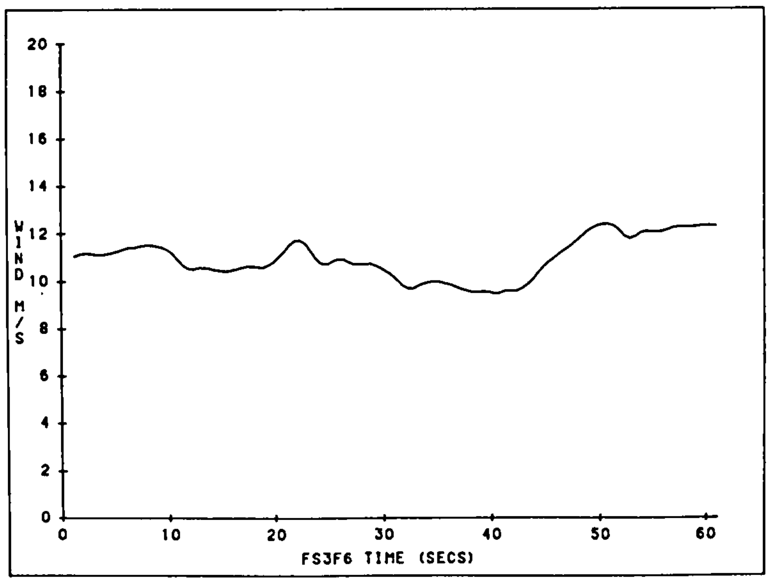
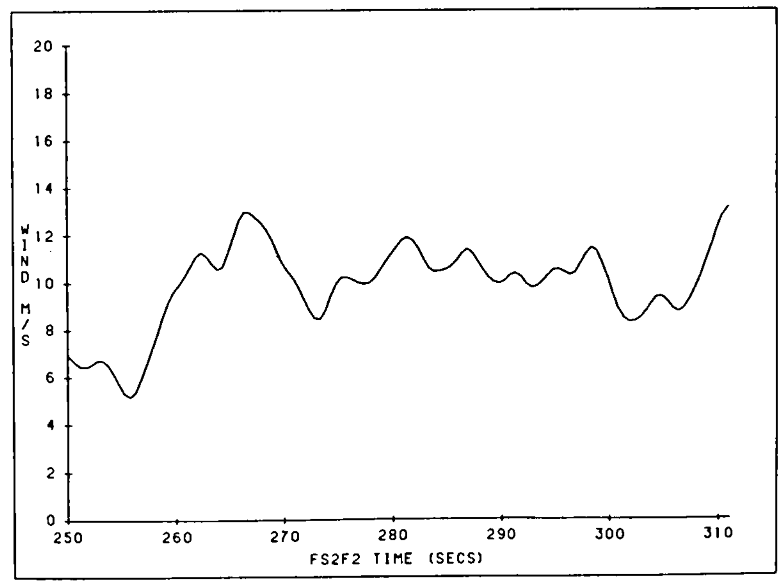


Figure D5-8



Nacelle Wind Speeds

Figure D5-10

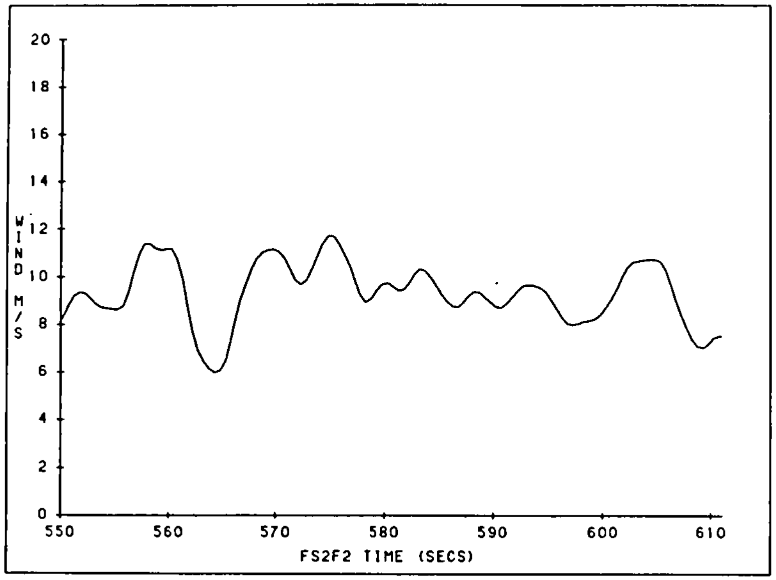


Figure D5-11

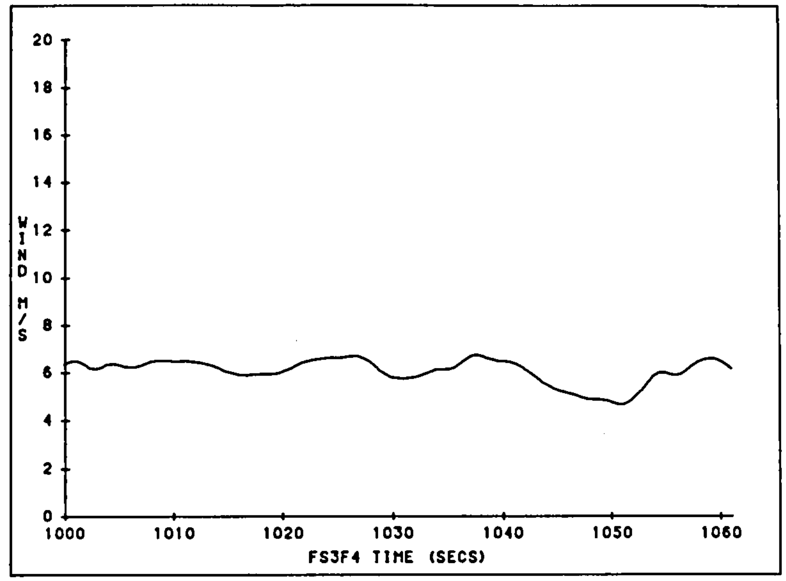


Figure D6-2

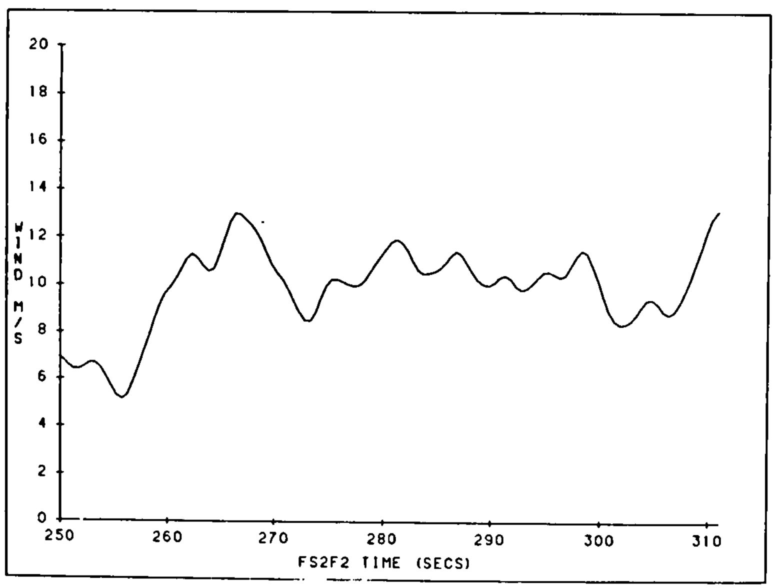


Figure D6-1

Nacelle Wind Speeds

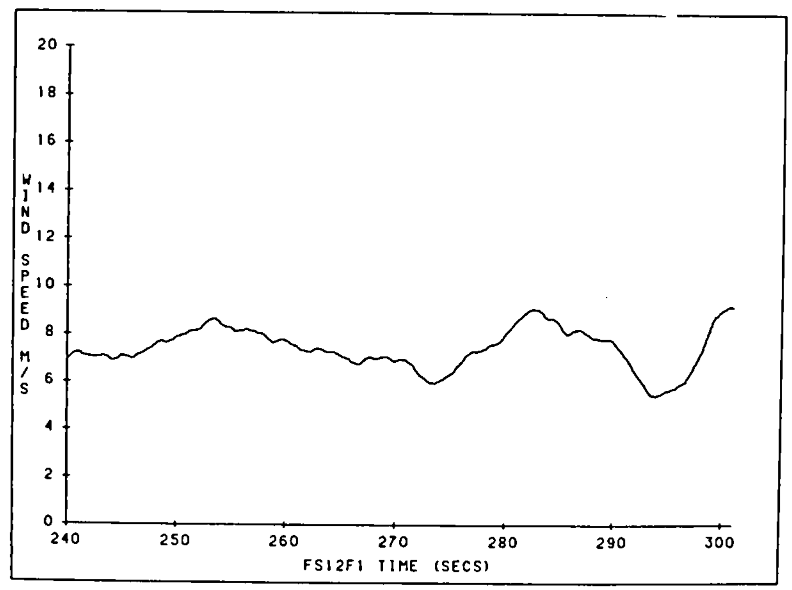


Figure D6-3

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16. Abstract
In order to assess the performance of a MOD-OA horizontal axis wind turbine when connected to an isolated diesel utility, a comprehensive data measurement program was conducted on the Block Island Power Company installation on Block Island, Rhode Island. This report presents the detailed results of that program focusing on three principal areas of (1) fuel displacement (savings), (2) dynamic interaction between the diesel utility and the wind turbine, (3) effects of three modes of wind turbine reactive power control. The approximate two month duration of the data acquisition program conducted in the winter months (February into April 1982) revealed performance during periods of highest wind energy penetration and hence severity of operation. It is concluded that even under such conditions fuel savings were significant resulting in a fuel reduction of 6.7% while the MOD-OA was generating 10.7% of the total electrical energy. Also, electrical disturbance and interactive effects were of an acceptable level.

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