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CONTROL SYSTEM DESIGN FOR THE MOD-5A 7.3 MW WIND TURBINE GENERATOR

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ABSTRACT

This paper provides descriptions of the requirements, analysis, hardware development and software development phases of the Control System design for the MOD-5A 7.3 MW Wind Turbine Generator. The system, designed by General Electric Company, Advanced Energy Programs Department, under contract DEN 3-153 with NASA Lewis Research Center and DOE, provides real time regulation of rotor speed by control of both generator torque and rotor torque. A variable speed generator system is used to provide both airgap torque control and reactive power control. The wind rotor is designed with segmented ailerons which are positioned to control blade torque. The central component of the control system, selected early in the design process, is a programmable controller used for sequencing, alarm monitoring, communication, and real time control. Development of requirements for use of aileron controlled blades and a variable speed generator required an analytical simulation that combined drivetrain, tower and blade elastic modes with wind distrubances and control behavior. An orderly two phase plan was used for controller software development. A microcomputer based turbine simulator was used to facilitate hardware and software integration and test.

INTRODUCTION

The MOD-5A Wind Turbine Generator design program was started in July, 1980. After conceptual design and preliminary design phases were completed, the MOD-5A configuration was rated at 7300 KW and featured a synchronous generator and two-speed rotor operation through a shiftable gearbox.

When final design and procurement started, it was found desirable to minimize the gearbox complexity and to provide a drivetrain back-torque during controlled shutdowns. The latter reduced cyclic loads that were design drivers for the aerodynamic partial span control. A variable speed generator subsystem was selected to meet these needs. The partial span control was subsequently replaced with an aileron control, and the variable speed generator subsystem provides a startup assist by motoring the rotor.

The MOD-5A design was performed under Contract DEN 3-153 for NASA Lewis Research Center and DOE by General Electric Company, Advanced Energy Programs Department.

MOD-5A SYSTEM

The MOD-5A model 304.2 system, operating parameters and features are shown in Figure 1. Control logic is provided by a programmable controller located in the nacelle. Operator control terminals are located at ground level in a separate building and remotely at a utility dispatch site. Automatic control of the MOD-5A operation provides for high availability and good energy capture in the NASA design wind regime and other wind regimes.

REQUIREMENTS

The control system of the MOD-5A was required by the design statement of work to:

- provide automatic unattended failsafe operation of the wind turbine
- provide ground level manual control for checkout and maintenance
- provide power quality acceptable to a utility
- provide remote dispatcher monitoring and control

Internal requirements were also established. Experience with MOD-1 indicated critical control multiplexing through sliprings should be avoided. A purchased controller with sensor and control interface software and hardware was desirable for initial units to permit concentration on the application process control software.

DEVELOPMENT PLAN

The development and configuration control planning established a two phase software development. During the first phase, a target controller hardware, a software development unit, and a wind turbine simulator were used to design, develop, code, debug, integrate, and checkout a full controller software package. This initial package was based on preliminary issued control system requirements. In parallel with the first phase development, control system analysis and wind turbine hardware design activities were ongoing. Design change requirements were accumulated, but not implemented during the first phase of software development.

The second phase of control system development incorporated the final control system requirements into hardware and software. A large portion of the first phase software was included and streamlined as a result of development experience. As major changes occurred in the MOD-5A configuration prior to the final requirements, this two phase plan worked well.

CONTROL PLAN

The system control plan for the MOD-5A model 304.2 is shown in Figure 2. This emphasizes the rotor and drivetrain control functions. Active control functions and critical sensors are shown in Table 1. Speed is the primary controlled parameter, using both ailerons to control wind torque at the rotor and a cycloconverter in the variable speed generator subsystem to control generator airgap torque. The utility reactive power or voltage is also controlled by the cycloconverter.

AILERON CONTROL

Aileron control of rotor torque was introduced to MOD-5A in mid-1983 with model 304.2. A 40% chord, 40% span plain aileron arrangement is used. Control properties were developed from wind tunnel test data. Three mechanically independent aileron sections, each driven by a hydraulic actuator, are used on each blade. An emergency accumulator is mounted with each actuator. Position servo loop electronics and valving, position sensing, and a latch are built into each actuator. The main hydraulic supply is mounted on the rotor support yoke with blade isolation check valves. The controller sends position commands to aileron pairs, such as both tip sections, and compares feedback positions signals to detect servo errors. A rotor stopping brake at the yoke is used to reach a full stop as the ailerons are not predicted to completely halt the rotor.

The rotor operating map is shown in Figure 3. These characteristics are included in the simulation model which is described later. Aileron control is used above 3 rpm to control rotor speed until the generator is synchronized. Generator airgap torque control holds system speed for wind speeds less than rating, including an automatic speed change from low range to high range. For wind speeds above rating, the aileron control holds rotor torque at the rated level of 3.38 million foot-pounds.

GENERATOR CONTROL

The MOD-5A variable speed generator susbsystem is a Scherbiustat type drive comprised of a wound rotor or doubly fed induction machine and a rotor circuit cycloconverter. The speed-power envelope for the subsystem is shown in Figure 4. The rotor circuit is rated at 1500 KVA, 20% of the total power rating. This permits generating operation of the wind rotor from below 12 rpm to about 17.5 rpm. The generator has 6 pole construction with a 60 Hz synchroneous speed of 1200 rpm.

The cycloconverter controller responds to torque and reactive power reference signals. It provides quadrature control of thyrister firing to maintain both generator power angle and excitation level. Feedback signals are supplied from generator speed, bus voltage, bus current, and stator current. The wind turbine speed controller drives the torque reference in proportion to speed error, as shown in Figure 4. This provides a speed-torque characteristic similar to a 3.5% slip machine, which damps the drivetrain oscillatory modes.

The speed controller reference is slowly moved automatically between the high and low speed ranges, depending on average power output. This keeps the wind rotor in an efficient tip speed range, as illustrated in Figure 3. The steady aileron position and output power versus wind speed are shown in Figure 5.

PERFORMANCE SIMULATION

An analytical model of the MOD-5A drivetrain control and tower bending modes is shown in Figure 6. This is a much simpler model than the dynamics model used to predict system frequencies and loads. The controls model includes a two inertia drivetrain and models the first blade flap elastic mode and the tower bending mode.

The bending modes are excited by rotor thrust changes arising from wind disturbances and aileron control action. As the MOD-5A aileron control is not used to provide drivetrain damping, the possibility of interaction with the tower bending mode was minimized, but the degree of freedom was retained in the model. The drivetrain and tower bending mode damping coefficients are small and these modes will oscillate if excited.

ROTOR SPEED CONTROL LOOP

A linearized rotor speed control loop in Z transform notation is shown in Figure 7 for a 40 mph operating condition. The block diagram indicates the digital and analog parts of the loop. Elements to the left of the vertical dashed line are carried out in the wind turbine controller, which has a cycle time of 0.1 seconds. The control algorithm has an integral gain of 5°/sec/rpm and a proportional gain of 30°/rpm, implemented digitally. A deadband of ± 0.07 rpm is used with the proportional gain to avoid steady oscillation from wind turbulence. The overall gain is varied with aileron position to keep loop gain constant. Digital clamps are provided to prevent integrator wind-up and to limit the aileron position command, but are not shown in the diagram.

The aileron servo-actuator response is represented as a 5 rad/sec. first order characteristic. Rate limits are used in the time domain representation. Mechanical elements include the slope of the aerodynamic torque vs. aileron position curve, system inertia, and a complex pole-zero from the generator inertia outside the control loop. This is an off-line model and does not include the airgap torque control loop, which looks like a viscous damper.

Speed feedback design used a digital sensor that counts toothed wheel magnetic pickup pulses over 0.05 seconds and periodically updates the value sent to the controller. The controller's analog to digital conversion time and memory update time are also included in the loop model.

The Bode plot in Figure 7 shows both the ideal analog model characteristics and the additional phase shift introduced by the digital time delays. A bandwidth of 1 rad/sec. is used for the rotor control loop. The 58° phase margin and 16 dB gain margin indicate the gain could be raised 10dB if necessary. Minimum requirements are 30° phase margin and 6 dB gain margin.

GENERATOR SPEED CONTROL LOOP

The generator linearized speed control loop characteristics are shown in Figure 8. This loop has a bandwidth of 17 rad/sec., which is too fast for implementation within the controller 0.1 second cycle time without unacceptable phase shift. The error summing junction and torque reference are provided by an analog circuit which obtains its speed reference from the controller. Operation of the cycloconverter and the generator rotor electrical dynamics is modeled as an 80 rad/sec. first order characteristic.

Ample gain and phase margins are evident in the Bode plot. Interaction with the rotor speed control loop is negligible with the large bandwidth difference. The closed loop characteristics of the generator speed control loop are mechanically similar to a high slip induction generator. By changing the proportional gain term, the effective slip is changed, within limits imposed by the mechanical frequencies of the wind turbine structure.

The cycloconverter torque reference signal is scaled from 40% of rated torque in a motoring direction to 120% of rated torque in a generating direction. When the aileron control is operating to maintain steady state rated torque, the damping effect of the generator speed-torque slope is active. With the scaling, maximum transient torque is limited to 120% of rating on an infrequent basis.

A more complex generator and cycloconverter model was also prepared as generally described in Reference 2. This model includes the electrical dynamics of the generator and the quadrature controller and is used to determine voltage and reactive power, as well as real power conditions. It will not be further described in this paper.

TIME DOMAIN SIMULATION RESULTS

The controls analysis simulation model was used to examine transient response of the MOD-5A wind turbine. Response to a 5 mph wind step is illustrated in Figure 9. Wind steps are not real phenomenon, but a step input excites all response modes and provides insight into response characteristics. The lightly damped tower bending mode is seen in Figure 9, set c. Clamping of the generator airgap torque is seen in set b. When the torque is clamped, the damping provided by the generator control is no longer present and the torque discontinuity slightly excites a generator inertia oscillation. Note that the aileron response to the rotor speed controller, shown in Figure 9, in set d, is not noticeable until 1.5 seconds after the step. The proportional control deadband limit was reached at this point and the proportional gain path became active.

The response to a sinusoidal wind gust is shown in Figure 10. A fully immersed rotor model is used. The 9 mph, 12 second gust is a far more severe event than found in nature. Initial transient response is similar to that observed for the wind step, but there is an undershoot when the distrubance returns to the original steady wind value. The speed swing is more severe than occurred with the wind step.

Note in Figure 10, set b, that total output power follows the speed oscillation as generator rotor power varies with speed. Stator power represents airgap torque and is clamped for the initial portion of the response.

Aileron response is outside the proportional deadband from 4 to 11 seconds and from 12 to 13 seconds, as shown in set d of Figure 10. The slower acting integral aileron control returns the system to initial conditions in less than 60 seconds.

A more realistic steady wind is illustrated in Figure 11. The NASA interim turbulence definition produces significant excitation at even multiples of the rotor speed. The sinusoidal gust noted in Figure 10 is also applied in Figure 11. A twice per revolution forced response is observed in all but the final aileron position and rate traces. This illustrates the beneficial effect of the aileron proportional deadband. Without the deadband, the aileron control would respond to the speed oscillation and cause unacceptable wear and maintenance. The deadband value would be field adjustable to match site turbulence characteristics.

A steady drivetrain and output power oscillation of about 10% peak to peak results from the turbulence model. Fatigue design of the drivetrain includes this and larger wind induced stress ranges. If necessary, the generator controller torque-speed slope could be field adjusted to reduce this amplitude.

Finally, a loss of load transient from a rated wind condition of 32 mph is illustrated in Figure 12. The generator airgap torque drops to zero and the generator inertia oscillates in a lightly damped manner around the rotor inertia. Rotor speed increases enough to drive the aileron actuators at their 5°/second limit for almost 7 seconds, as shown in Figure 12, set d. Maximum rotor speed is about 18.25 rpm. Software and failsafe hardware overspeed trip points were defined above this transient overspeed to avoid nuisance shutdowns to lockout which would require a site maintenance visit.

The transient response analyses also included down gusts, as well as up gusts and examined all wind speed conditions. Time delay effects and controller gains were defined on the basis of these analyses.

CONTROL SYSTEM ARRANGEMENT

A simplified block diagram of the MOD-5A control system is shown in Figure 13. The number of command and sensor signals that each line represents is noted. An "S" indicates a digital serial data signal. Over 70% of the signals to the controller are from the nacelle and rotor which is why the main controller cabinet is located in the nacelle. The three serial data links are not time- critical to wind turbine control.

The emergency shutdown panel is a relay logic circuit that provides deadman type initiation of aileron controlled shutdown if the main controller or critical backup sensors indicate a failure. This panel also causes a shutdown if control power is lost.

A further backup emergency shutdown (BESD) circuit to detect overspeed is mounted on the rotor. Each blade has an acceleration or g-switch that is oriented radially to respond to speed. The switch circuit is independent of the emergency shutdown panel. All aerodynamic control functions are tested automatically before every MOD-5A startup. The aileron servo actuators are used to move the control surfaces and each emergency shutdown circuit is operated to assure return to full aileron deployment. A test circuit is included in the g-switches to check both minimum and maximum trip levels on each startup.

Ground control equipment is housed in the electrical equipment building shown in Figure 14. The variable speed generator subsystem cycloconverter and isolation transformer are shown at the right, with the 4160 volt switchgear. Auxiliary power distribution and control connection cabinets are to the left. Batteries are mounted in a separate, vented area. A small office area contains the system disply panel, site operator terminal, and engineering data equipment.

The system display panel is shown in Figure 15. It provides a panic button and master key control panel at the upper left. Two closed circuit video monitors are included in the first unit design. One camera observes the interior of the nacelle and the other views the rotor. The right panel provides switch controlled digital meters for quick observation of operating conditions and electrical status.

The main controller equipment shown in Figure 16 is mounted in a double bay cabinet in the nacelle. An air to air heat exchanger cools the cabinet without a refrigerant cycle for higher availability. The cabinet air is internally circulated, but is not connected to outside air. In addition to the controller equipment and interface modules, sensor conditioning circuits are installed in the controls equipment cabinet.

CONTROLLER DEVELOPMENT

Controller hardware and software development followed the two phase plan noted in a prior paragraph. The plan permitted accommodation of the major changes that occurred when the variable speed generator and ailerons were introduced into the system design.

Equipment selection was made early and a target controller hardware assembly was procured for development use. Controller requirements are shown in Table 2. A single board computer system meets most of the requirements, but would have required more integration effort than planned. A high-end programmable controller, the Eagle Signal Eptak 700, was selected. It has multiple coding language capability and a proven industrial reliability record. With the tremendous growth in microcomputer based equipment, more equipment choices are now available than when the MOD-5A equipment selection was made. An updated selection was not made for the first few units because of the software development investment.

A wind turbine simulator was developed using another programmable controller, the Analog Devices MACSYM 2 and a custom analog board. The simulator provided sensor inputs and simulated operation of the MOD-5A to the controller. It was valuable in debugging and testing the integrated controller software.

Controller development milestones are shown in Table 3. A fully integrated software package was completed and is ready for wind turbine hardware integration.

Software modes are shown in Figure 17. Vendor software provides real world signal interfacing with controller memory, real time clock values, and the master operating system. Application software is used to initialize outputs and variables on a cold start, execute on a 0.1 second real time basis and properly sequence through the main program modules.

The main program modules are as follows:

- Input Signal Manager (ISM)
- Data Processing
- Mode Logic
- Data Archive
- Power Generation
- Manual
- Communication
  - Remote Terminal
  - Site Terminal
  - Control Data System (CDS)
- Startup
- Ramp
- Yaw
- Alarm
- Normal/Emergency Shutdown
- Rotor Hydraulic Pump Module
- Output Signal Management (OSM)
- Memory Test (background)

The data processing module computes averages, adds signal biases, and packs data. Mode logic establishes flags for the executive to determine which other modules to run. The manual module provides individual command outputs, with overall checking, in response to site terminal inputs.

Data archive uses over half of the random access memory (RAM) to store both a moving window of sensor data prior to a shutdown event, and also a window after the event. Lockout events require personnel at the site to command a restart and the restart software requires an archive dump. The archive data will assist in trouble shooting and maintenance. A memory test module operates in whatever time is not being used for control functions and sequentially checks RAM.

OPERATOR INTERFACE

Both the site and remote standard operator devices are 300 baud printing terminals. They provide a log of operation on event, demand, or time. A sample output is shown in Figure 18. Alarm outputs are noted when states change and command inputs are time tagged. The controller does not rely on a continuously active terminal, but may be modified to require this. If the terminal is shut off, the log data is sent out by the controller, but will be lost.

In place of the standard phone line remote terminal serial link, a parallel control and data interface may be used at the MOD-5A site. A parallel interface was planned for the Hawaiian Electric Company, (HECO), with an operator interface through the HECO dispatch computer using microwave transmission of data through a HECO multiplexor.

DEVELOPMENT RESULTS

Controller software was successfully integrated and checked out using the development controller and simulator. A timing check of the worst condition was made. It took 89 msec. to execute within the desired 100 msec. executive time cycle. The control subsystem specification requires less than 200 msec. so ample margin is evident. A normal cycle takes 83 msec., of which 10 msec. is from the controls data system, which is not permanently installed.

Application memory was planned at 20K bytes of programmable read only memory (PROM) and 20K bytes of RAM. Actual usage was 17.7K PROM and 17.3K RAM. 14K of the RAM usage is for archive data storage. Adequate margin exists for changes during hardware integration and field checkout.

Simulator outputs are shown in Figures 19, 20 and 21. A normal startup and power generation in an increasing wind is shown in Figure 19. There are three aileron movements of about 30° at symbol A during the startup check sequence followed by a motion to the startup angle. The rotor is motored to part speed, then the ailerons are active at B to control the rotor speed which follows an increasing reference. Synchronization and power generation occurs at C and the ailerons continue to their aligned position for maximum torque.

After the lower speed range is reached at D, wind speed steps were added at E, which first raise output power, then enter active aileron control at F. The power average causes automatic transition to the higher speed range at G. Continued wind steps above rating at H illustrate aileron control response. Random wind speed fluctuations are simulated and the power response is, therefore, oscillatory over a small range.

The yaw drive control sequences the push-pull hydraulic actuator and gripper drive system. A ratchet action occurs if there is a large yaw error as a full actuator stroke is only 10°. Response to large initial errors in both directions is shown in Figure 20. As the drive moves, the error is reduced. Motion occurs at 0.50°/second and the average continuous drive rate is just below 0.25°/second.

Finally, a yaw correction and a transition from electrical to aerodynamic torque control are illustrated in Figure 21. Random fluctuations in wind direction and speed are simulated.

CONCLUSIONS

The MOD-5A system and the control subsystem will provide well behaved performance in fluctuating winds. Analytical models are available for site specific performance analysis.

Software integration was completed successfully with the development controller and simulator. Timing and memory goals were met. The two phase development plan successfully accommodated major configuration changes.

The control subsystem was defined in detail with drawings and specifications and the software is ready for hardware integration.

ACKNOWLEDGEMENTS

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REFERENCES

1. Barton, R.S., Lucas, W.C. "Conceptual Design of the 6 MW MOD-5A Wind Turbine Generator", Proceedings of the Fifth Biennial Wind Energy Conference and Workshop, SERI/CP-635-1340, Vol 1, pp. 157-168, October 1981.
2. Mayer, C.B., "High Response Control of Stator Watts and Vars for Large Wound Rotor Induction Motor Adjustable Speed Drives", IEEE Transactions IAS79:27F, pp. 817-823.

Table 1- Active Control Functions

ROTOR

AILERONS - 3/BLADE, POSITION CONTROL
SPEED - REGULATED WITH AILERONS
TEETER BRAKES - TWO LEVEL CONTROL, ALARMS
STOPPING BRAKES - OFF/ON CONTROL
ROTOR HYDRAULICS - OFF/ON, ALARMS
G-SWITCH - BACKUP OVERSPEED SENSOR, TEST

NACELLE AND YAW

EMERGENCY SHUTDOWN PANEL - CONTROLLED BACKUP
GEARBOX LUBE - OFF/ON, ALARMS
GENERATOR LUBE - OFF/ON, ALARMS
YAW HYDRAULICS - OFF/ON, ALARMS
ROTOR POSITIONER - OFF/ON
YAW DRIVE - SEQUENCED OFF/ON CONTROL, ALARMS
GENERATOR SPEED - REGULATED WITH CONVERTER

GROUND AND ELECTRICAL

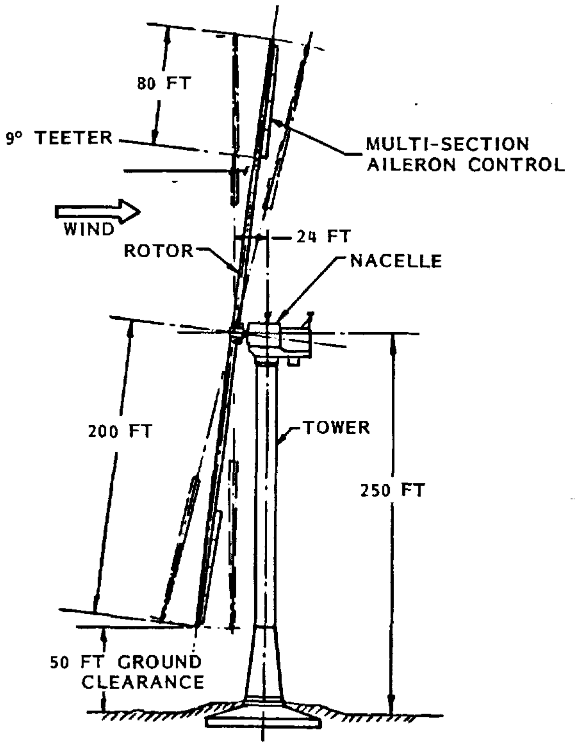
CYCLOCONVERTER - TORQUE CONTROL, VAR/VOLT CONTROL
SWITCHGEAR - TRIP/CLOSE CONTROL, ALARMS
INTRUSION ALARM
LOCAL OPERATOR CONTROL - ENABLE, SETPOINTS, DATA
REMOTE OPERATOR CONTROL - ENABLE, SETPOINTS, DATA

Table 2- Controller Hardware Requirements

• **INPUT SIGNAL**	- **19 ANALOG** - **69 DISCRETE (20 mA)**
• **OUTPUT SIGNAL**	- **6 ANALOG** - **26 DISCRETE (3A/20A)**
• **SERIAL COMMUNICATIONS**	- **(2) 20 mA 300 BAUD** - **(1) 20 mA 1200 BAUD**
• **CAPACITY**	- **64K** - **20K USER PROGRAM** - **20 K RAM** **8K ECL 3 & RAM** **16K I/O**
• **LANGUAGE**	- **ECL-3, ASSEMBLY**

Table 3- Control Subsystem Development Milestones

	COMPLETED CONCEPTUAL DESIGN	4/81
PHASE I		
	COMPLETED REQUIREMENTS FOR SYNCHRONOUS GENERATOR, PARTIAL SPAN CONTROL	7/81
	COMPLETED EQUIPMENT SELECTION FOR CONTROLLER AND SIMULATOR	1/82
	COMPLETED CODING	7/82
	COMPLETED SOFTWARE MODULE CHECKOUT	12/82
	COMPLETED SYSTEM INTEGRATION	4/83
PHASE II		
	COMPLETED REVISION A REQUIREMENTS FOR VARIABLE SPEED GENERATOR	7/83
	COMPLETED SOFTWARE DESIGN WITH REVISION B REQUIREMENTS FOR AILERONS	10/83
	COMPLETED CODING AND MODULER CHECKOUT	2/84
	COMPLETED SYSTEM INTEGRATION	4/84



OPERATIONAL CHARACTERISTICS

RATED POWER	7300 KW AT 0.98PF
RATED WIND SPEED	32 MPH AT 250 FT
CUT-IN/CUT-OUT WIND SPEED	14/60 MPH AT 250 FT
MAXIMUM WIND SPEED (SURVIVAL)	130 MPH AT 250 FT
POWER CONTROL	MULTI-SECTION AILERONS
ROTOR RPM-SET SPEED	13.7/16.8 RPM (± 10%)
ENERGY CAPTURE/YR	21.3 X 10^6 KWH (NASA SPECIFIED WIND SPEED DURATION CURVE, 14 MPH AT 32 FT, 100 % AVAIL)
TOTAL WT ON FOUNDATION	1804 K-LB

FEATURES

- WOOD LAMINATE BLADES WITH HIGH PERFORMANCE AIRFOIL - UPWIND, TEETERED
- NON-ROTATING ROTOR SUPPORT
- HYBRID EPICYCLIC/PARALLEL SHAFT GEARBOX
- VARIABLE SPEED/CONSTANT FREQUENCY OPERATION, WITH 2 SET POINTS
- SOFT SHELL TOWER, TUNEABLE BELL SECTION

Figure 1- MOD-5A System Model 304.2

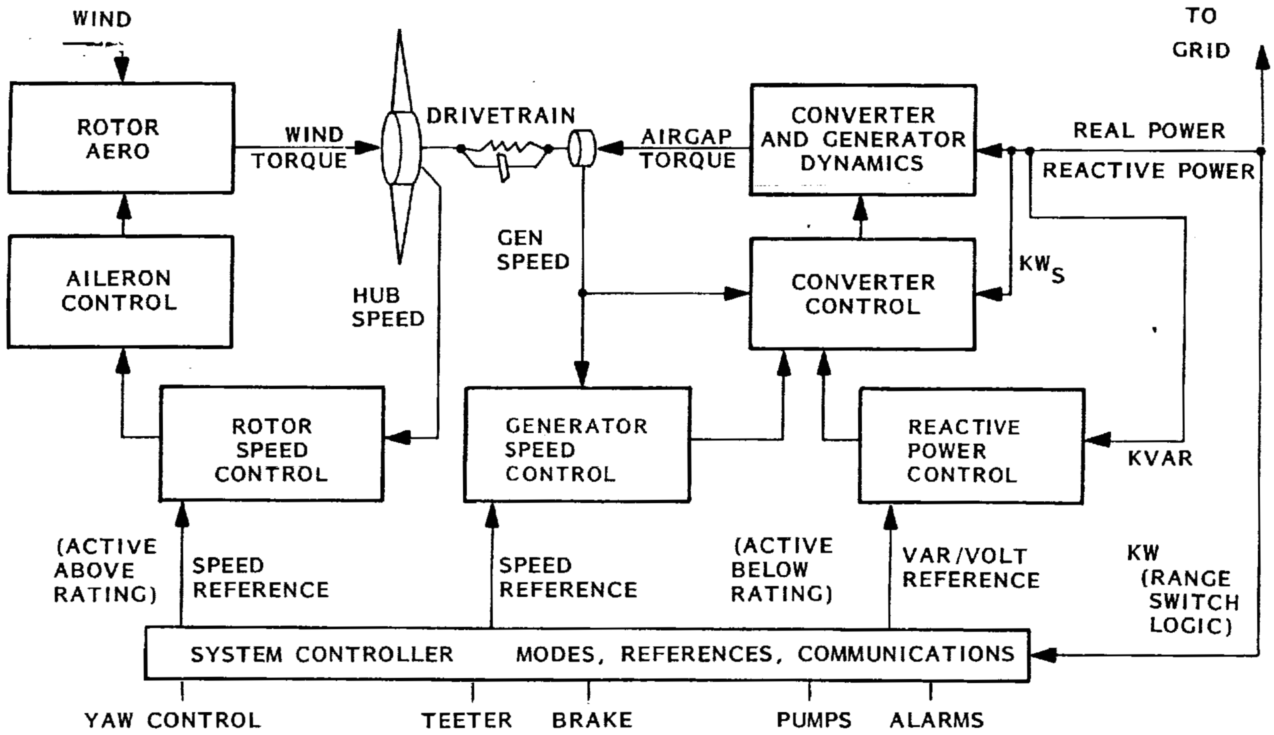


Figure 2- System Control Plan Block Diagram

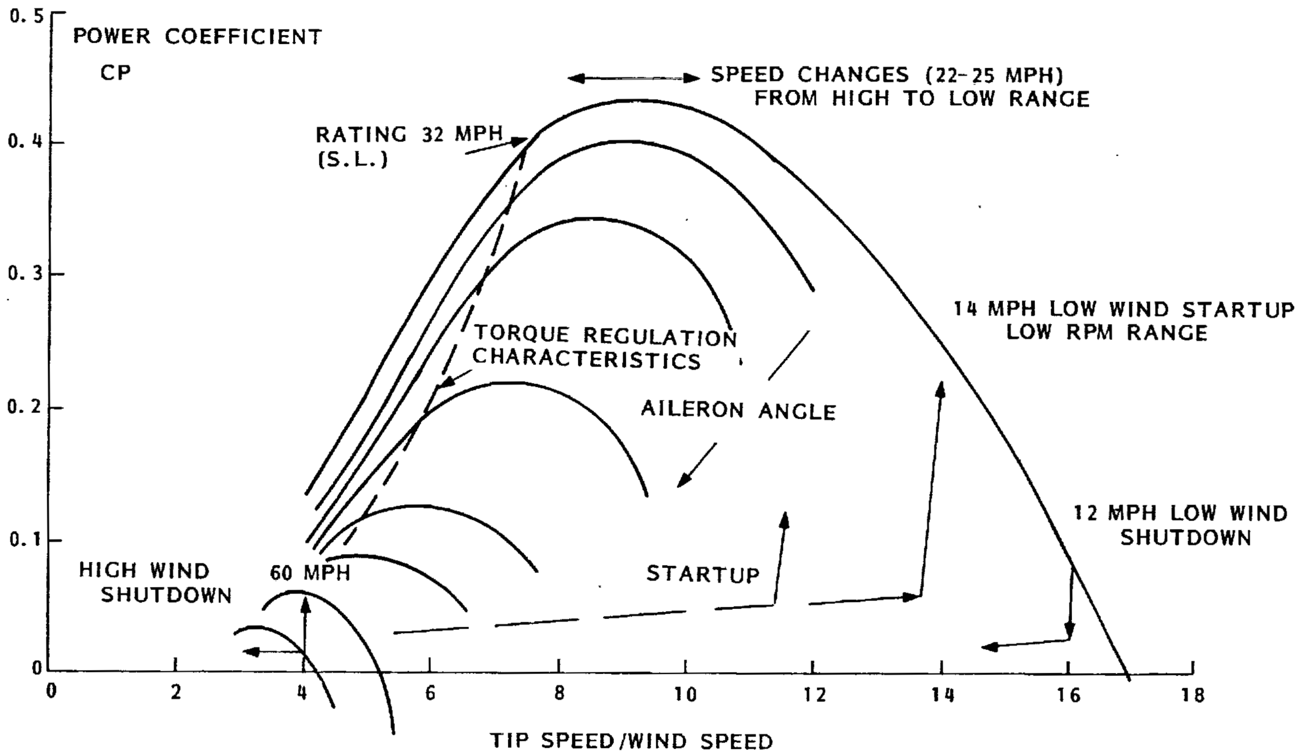


Figure 3- Rotor Operating Regime

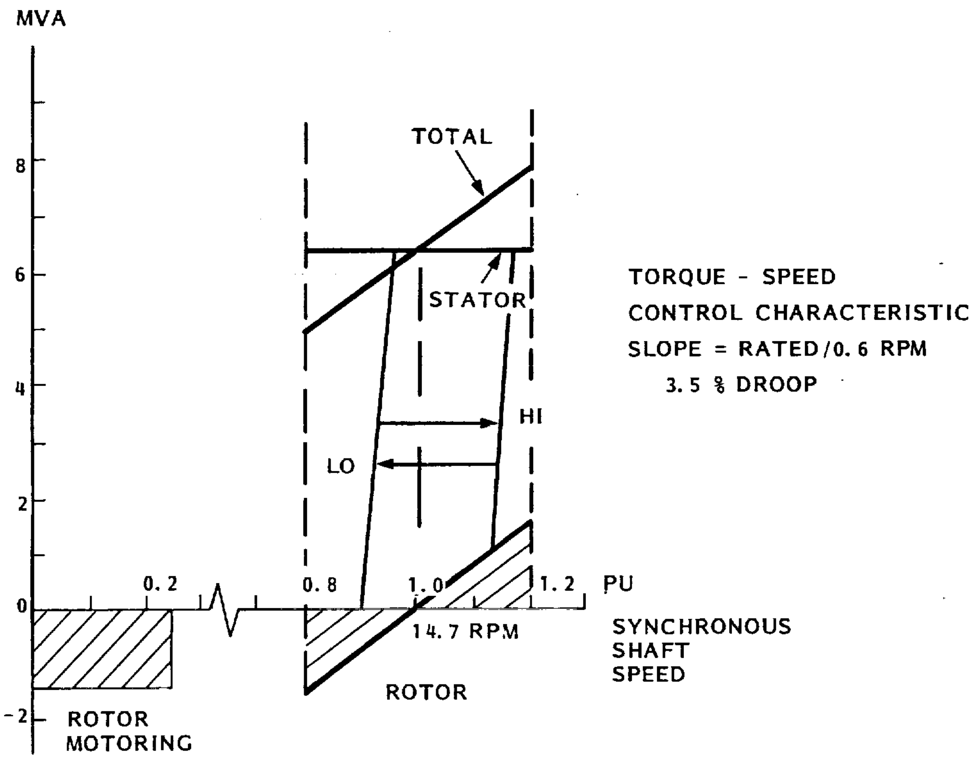


Figure 4- Generator Operating Regime

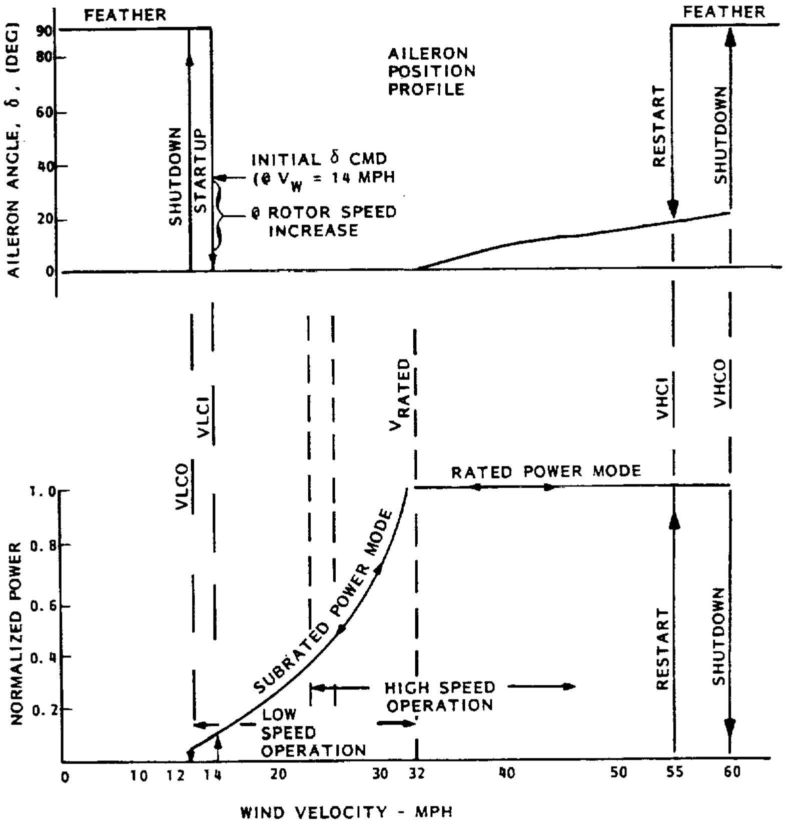
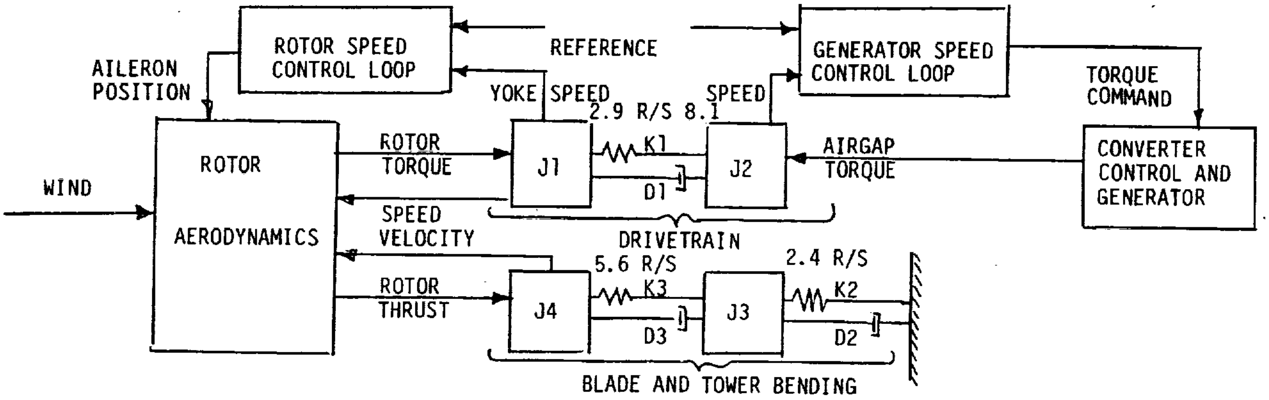


Figure 5- Aileron Position and Output Power Versus Wind Speed



J1 = Rotor Inertia	$40 * 10^6$ Slug-ft^2
J2 = Generator & High Speed Shaft, Inertia reflected to Rotor	$(745+30)(82.14)^2 = 5.2*10^6$ slug-ft^2
J3 = Tower Mass	$2.9 * 10^4$ slug
J4 = Blade Flap Mass	$1.06 * 10^3$ slug
K1 = Drivetrain Spring Constant	$3.38 * 10^8$ ft-lb/rad
K2 = Tower Spring Constant	$1.674 * 10^5$ lbs/ft
K3 = Blade Flap Spring Constant	$3.370 * 10^4$ lbs/ft
D1 = Drivetrain Damping Coefficient	$3.0 * 10^6$ ft-lb/(rad/sec)
D2 = Tower Damping Coefficient	6968 lb/(ft/sec)
D3 = Blade Flap Damping Coefficient	3785 lb/(ft/sec)

Figure 6- Simulation Model Diagram

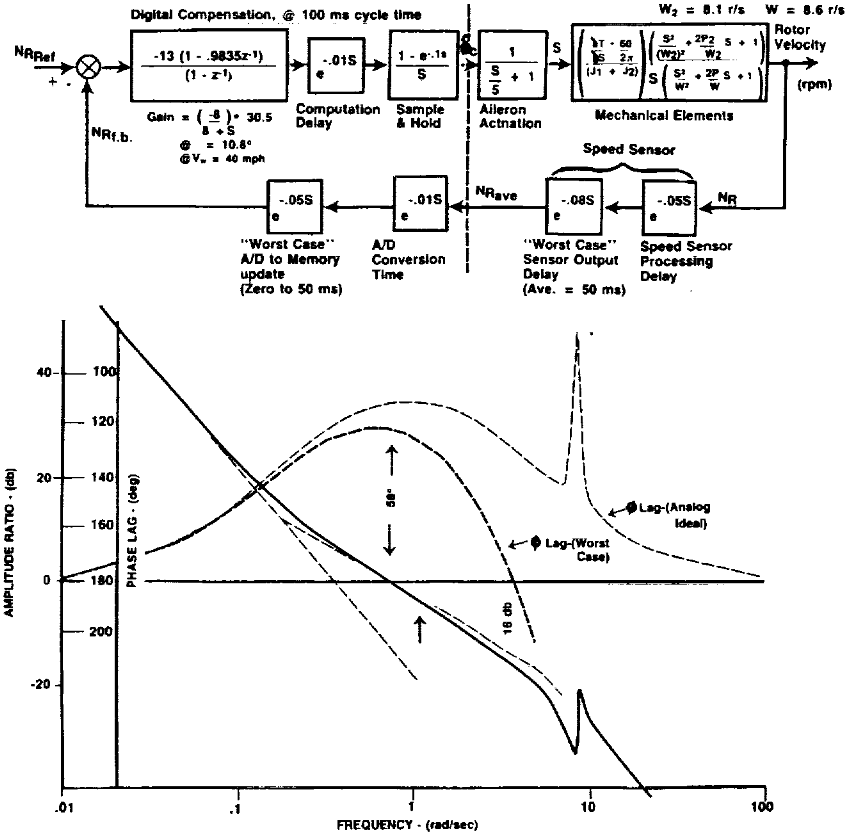


Figure 7- Rotor Speed Loop Characteristics

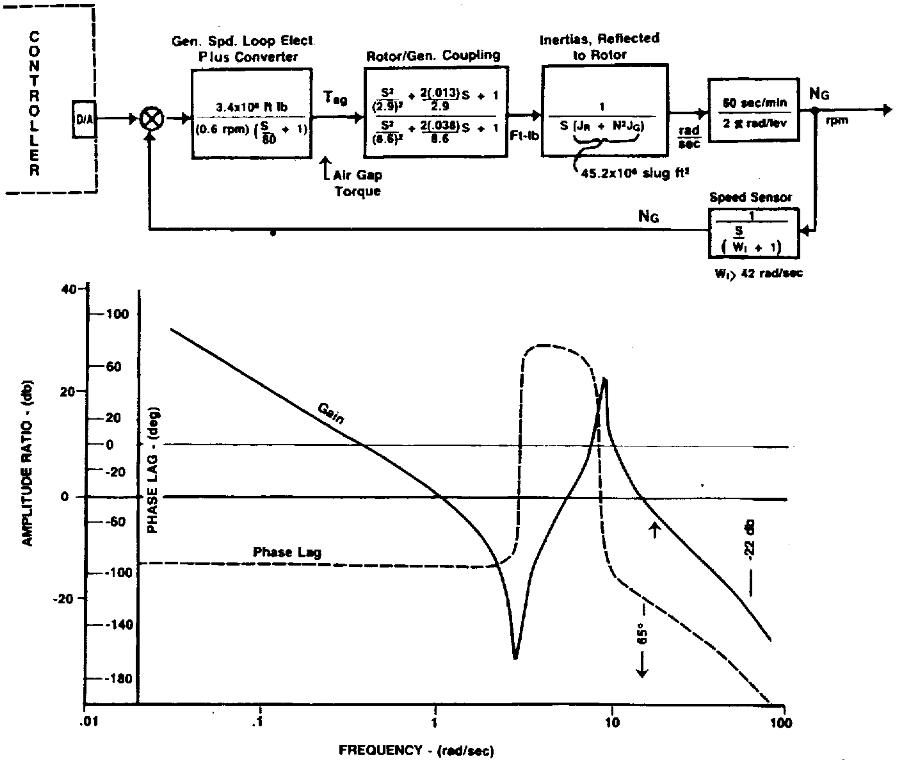


Figure 8- Generator Speed Loop Characteristics

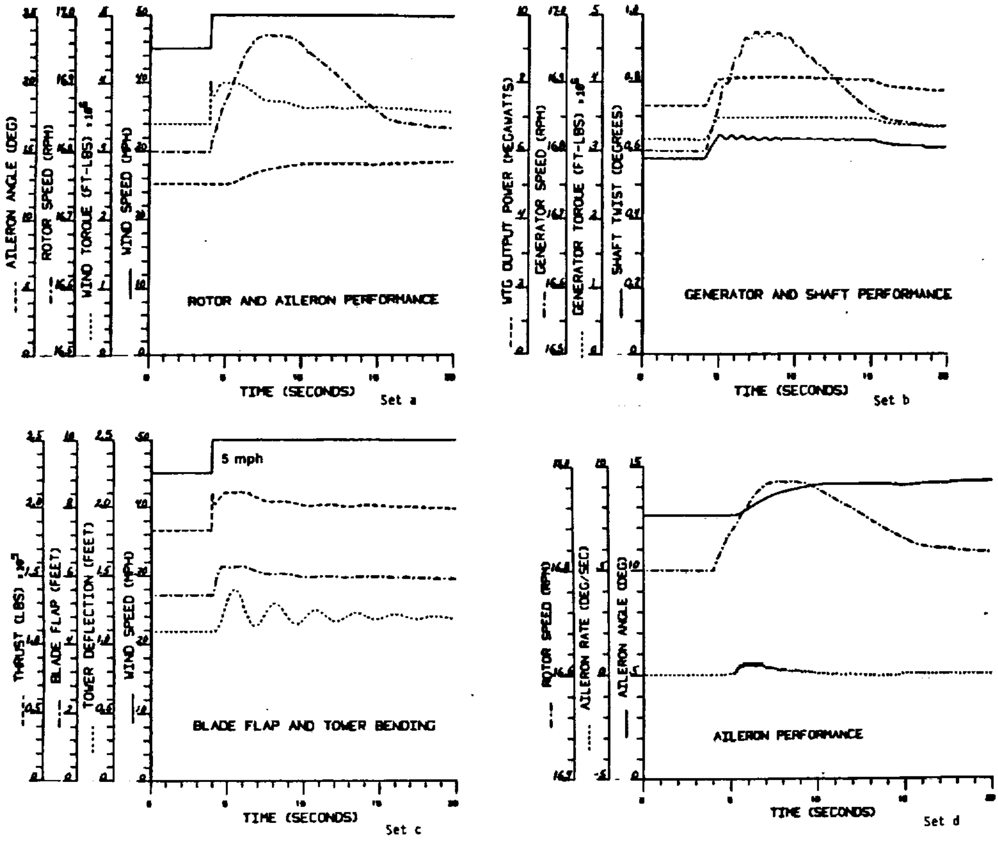


Figure 9- Response To Step Wind Change

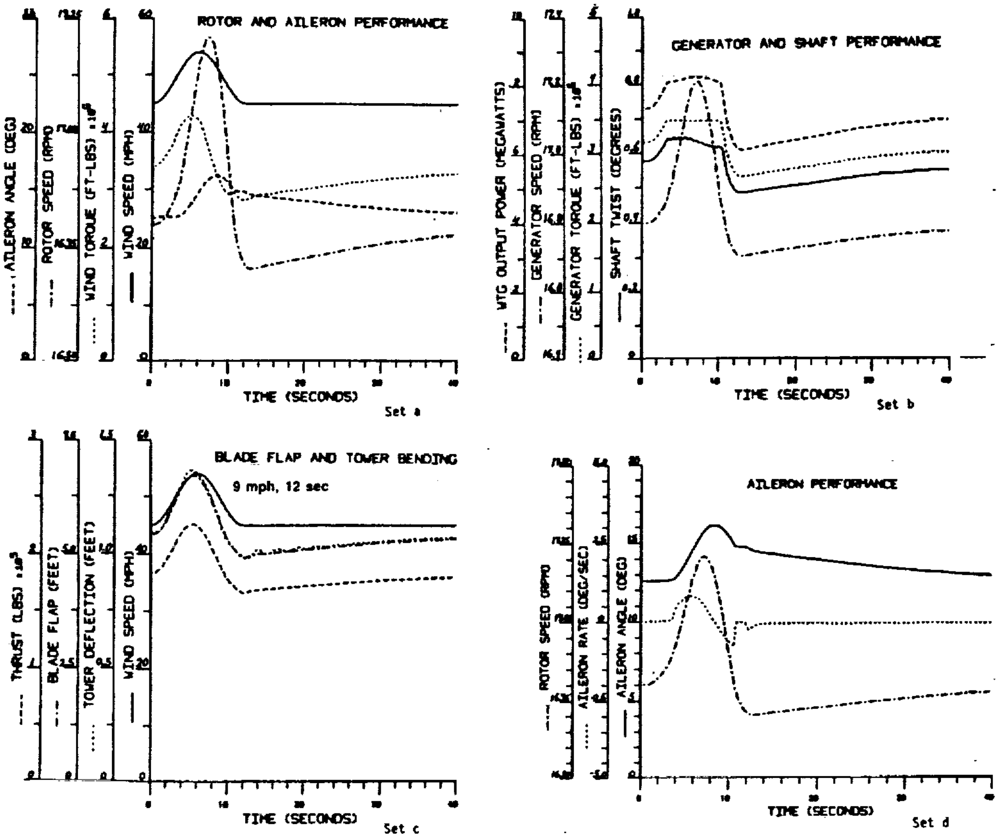


Figure 10- Response To 1-Cosine Wind Change

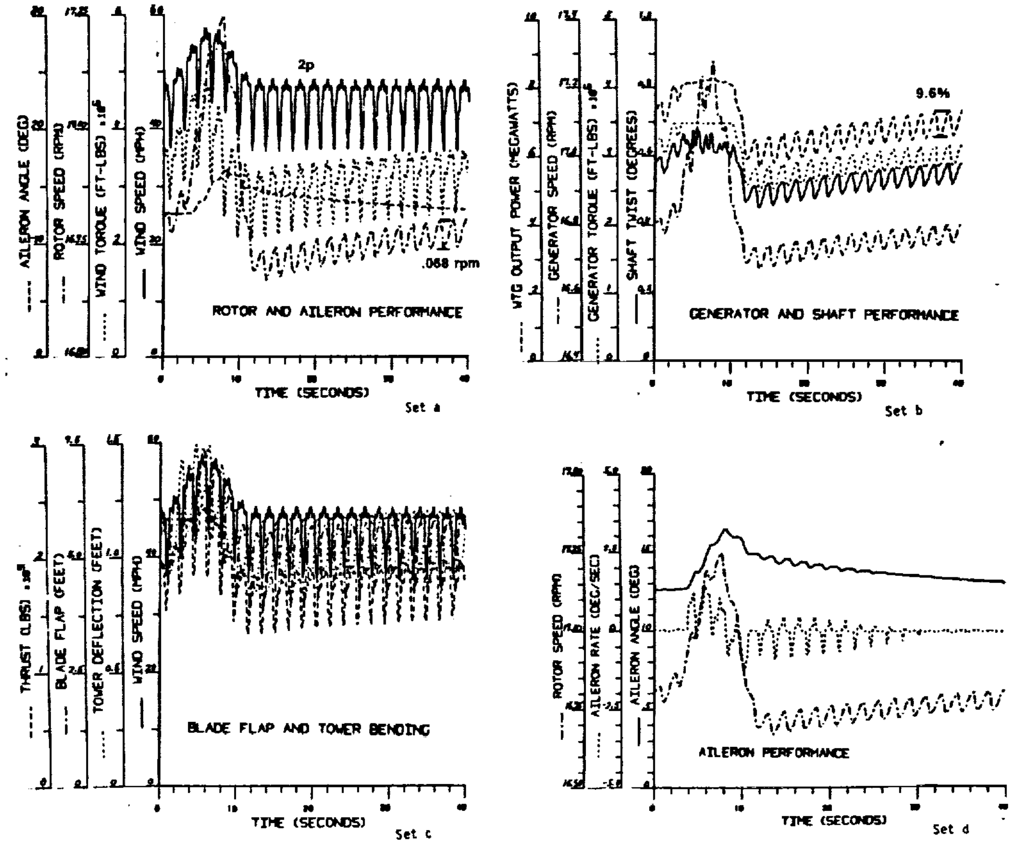


Figure 11- Response To 1-Cosine Wind Change Plus Turbulence

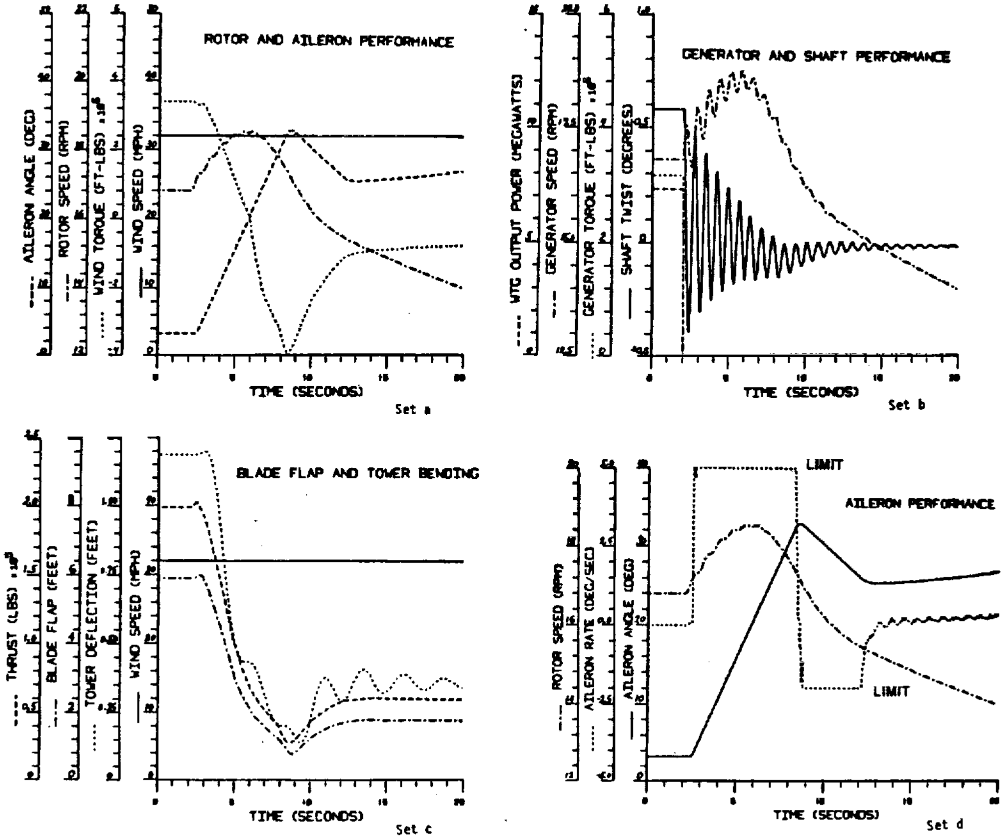


Figure 12- Response To Loss Of Load

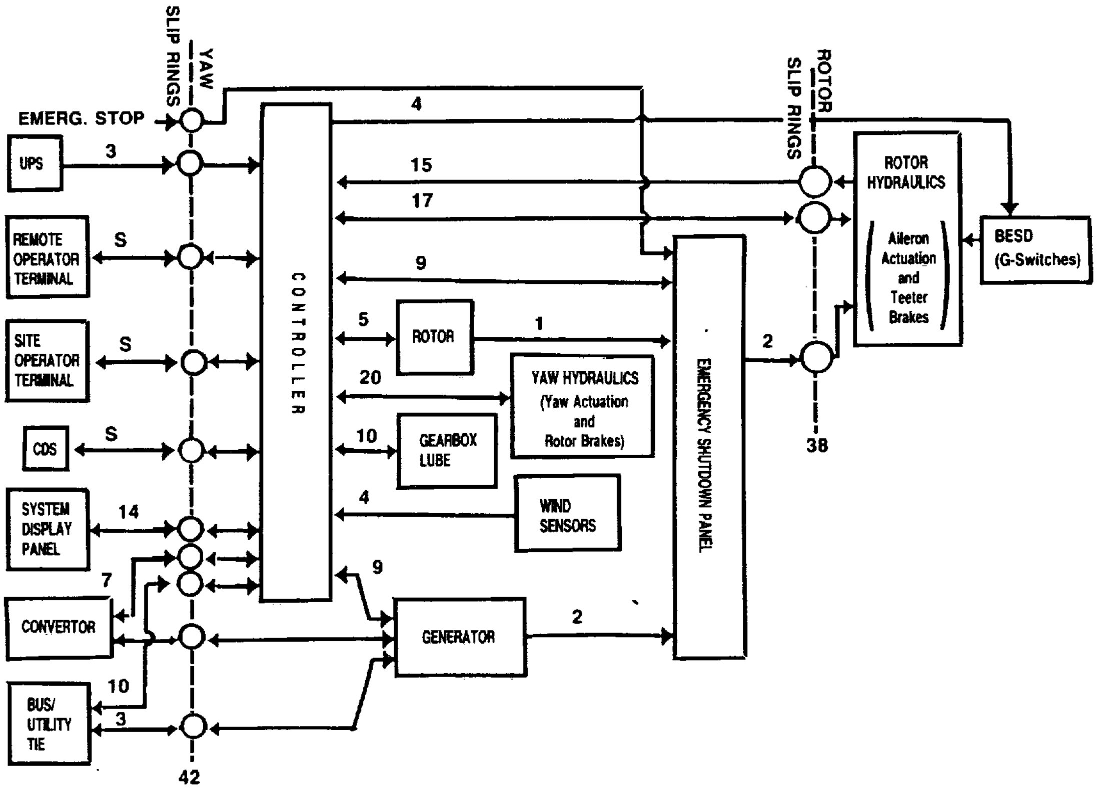


Figure 13- Control Subsystem Block Diagram

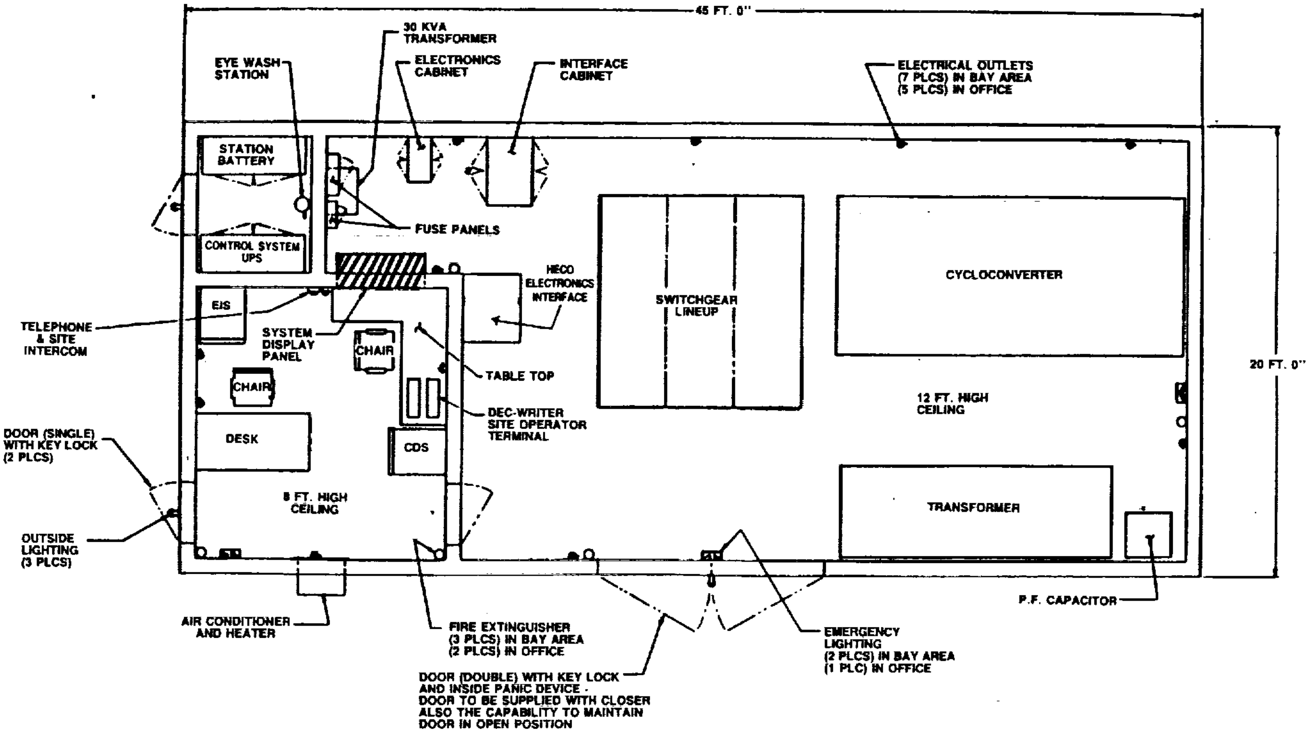


Figure 14- Electrical Equipment Building

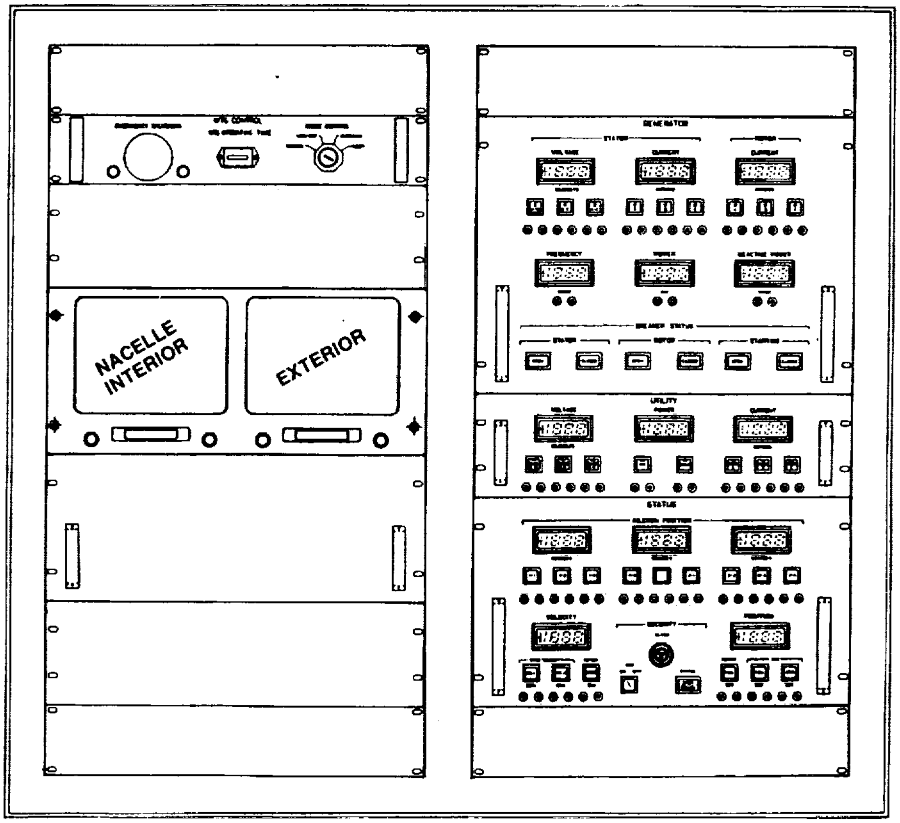


Figure 15- Operator Display Panel

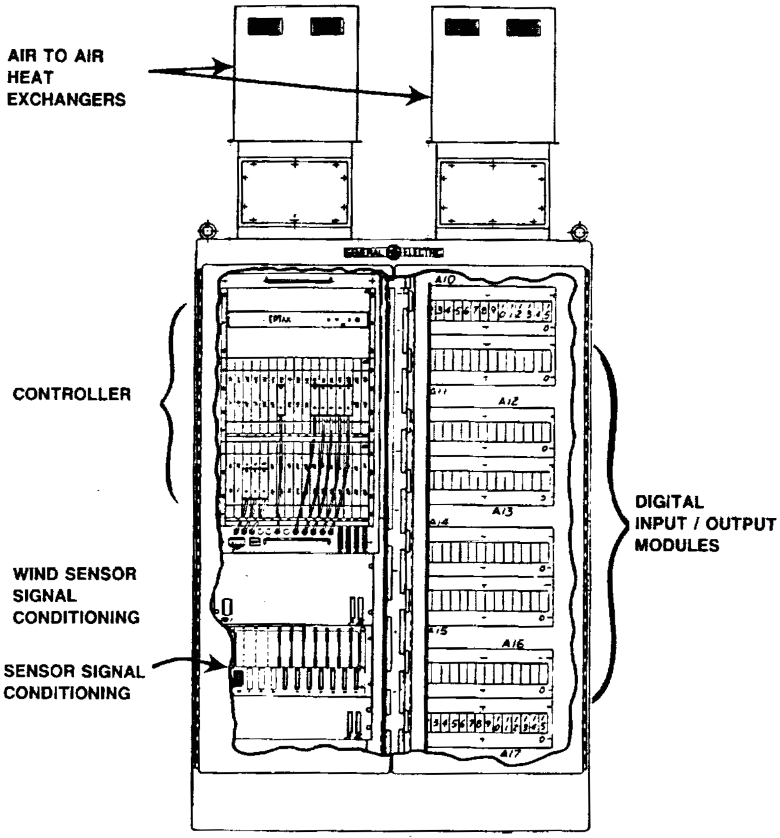


Figure 16- Nacelle Control Equipment Cabinet

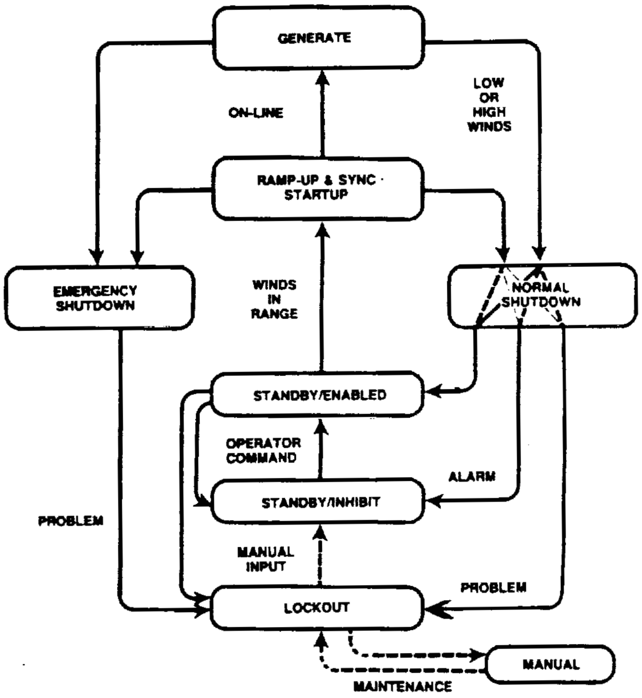
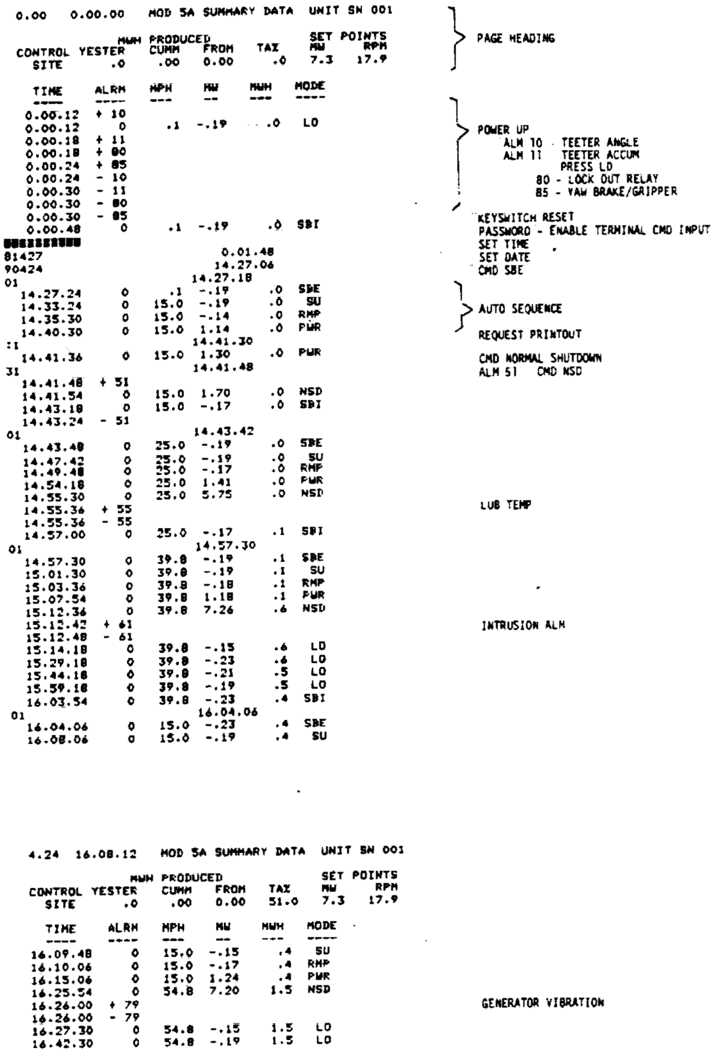


Figure 17- Software Control Mode Interaction



```
0.00   0.00.00   MOD 5A SUMMARY DATA  UNIT SN 001

                MWH PRODUCED                SET POINTS
CONTROL  YESTER   CUMM    FROM    TAX    MW      RPM          PAGE HEADING
  SITE       .0    .00    0.00     .0    7.3    17.9

   TIME      ALRM    MPH     MW     MWH    MODE
   ----      ----    ---     --     ---    ----
  0.00.12   + 10
  0.00.12      0      .1    -.19     .0    LO              POWER UP
  0.00.18   + 11                                              ALM 10   TEETER ANGLE
  0.00.18   + 80                                              ALM 11   TEETER ACCUM
  0.00.24   + 85                                                        PRESS LD
  0.00.24   - 10                                                     80 - LOCK OUT RELAY
  0.00.30   - 11                                                     85 - YAW BRAKE/GRIPPER
  0.00.30   - 80
  0.00.30   - 85                                           KEYSWITCH RESET
  0.00.48      0      .1    -.19     .0   SBI              PASSWORD - ENABLE TERMINAL CMD INPUT
[redacted]                                                 SET TIME
81427                      0.01.48                         SET DATE
90424                     14.27.06                         CMD SBE
01                       14.27.18
  14.27.24     0      .1    -.19     .0   SBE
  14.33.24     0    15.0    -.19     .0    SU              AUTO SEQUENCE
  14.35.30     0    15.0    -.14     .0   RMP
  14.40.30     0    15.0    1.14     .0   PWR              REQUEST PRINTOUT
:1                       14.41.30
  14.41.36     0    15.0    1.30     .0   PWR              CMD NORMAL SHUTDOWN
31                       14.41.48                          ALM 51   CMD NSD
  14.41.48  + 51
  14.41.54     0    15.0    1.70     .0   NSD
  14.43.18     0    15.0    -.17     .0   SBI
  14.43.24  - 51
01                       14.43.42
  14.43.48     0    25.0    -.19     .0   SBE
  14.47.42     0    25.0    -.19     .0    SU
  14.49.48     0    25.0    -.17     .0   RMP
  14.54.18     0    25.0    1.41     .0   PWR
  14.55.30     0    25.0    5.75     .0   NSD
  14.55.36  + 55                                           LUB TEMP
  14.55.36  - 55
  14.57.00     0    25.0    -.17     .1   SBI
01                       14.57.30
  14.57.30     0    39.8    -.19     .1   SBE
  15.01.30     0    39.8    -.19     .1    SU
  15.03.36     0    39.8    -.18     .1   RMP
  15.07.54     0    39.8    1.18     .1   PWR
  15.12.36     0    39.8    7.26     .6   NSD
  15.12.42  + 61                                           INTRUSION ALM
  15.12.48  - 61
  15.14.18     0    39.8    -.15     .6    LO
  15.29.18     0    39.8    -.23     .6    LO
  15.44.18     0    39.8    -.21     .5    LO
  15.59.18     0    39.8    -.19     .5    LO
  16.03.54     0    39.8    -.23     .4   SBI
01                       16.04.06
  16.04.06     0    15.0    -.23     .4   SBE
  16.08.06     0    15.0    -.19     .4    SU



4.24  16.08.12   MOD 5A SUMMARY DATA  UNIT SN 001

                MWH PRODUCED                SET POINTS
CONTROL  YESTER   CUMM    FROM    TAX    MW      RPM
  SITE       .0    .00    0.00   51.0    7.3    17.9

   TIME      ALRM    MPH     MW     MWH    MODE
   ----      ----    ---     --     ---    ----
16.09.48       0    15.0    -.15     .4    SU
16.10.06       0    15.0    -.17     .4   RMP
16.15.06       0    15.0    1.24     .4   PWR
16.25.54       0    54.8    7.20    1.5   NSD
16.26.00    + 79                                           GENERATOR VIBRATION
16.26.00    - 79
16.27.30       0    54.8    -.15    1.5    LO
16.42.30       0    54.8    -.19    1.5    LO
```

Figure 18- Sample Operator Terminal Output

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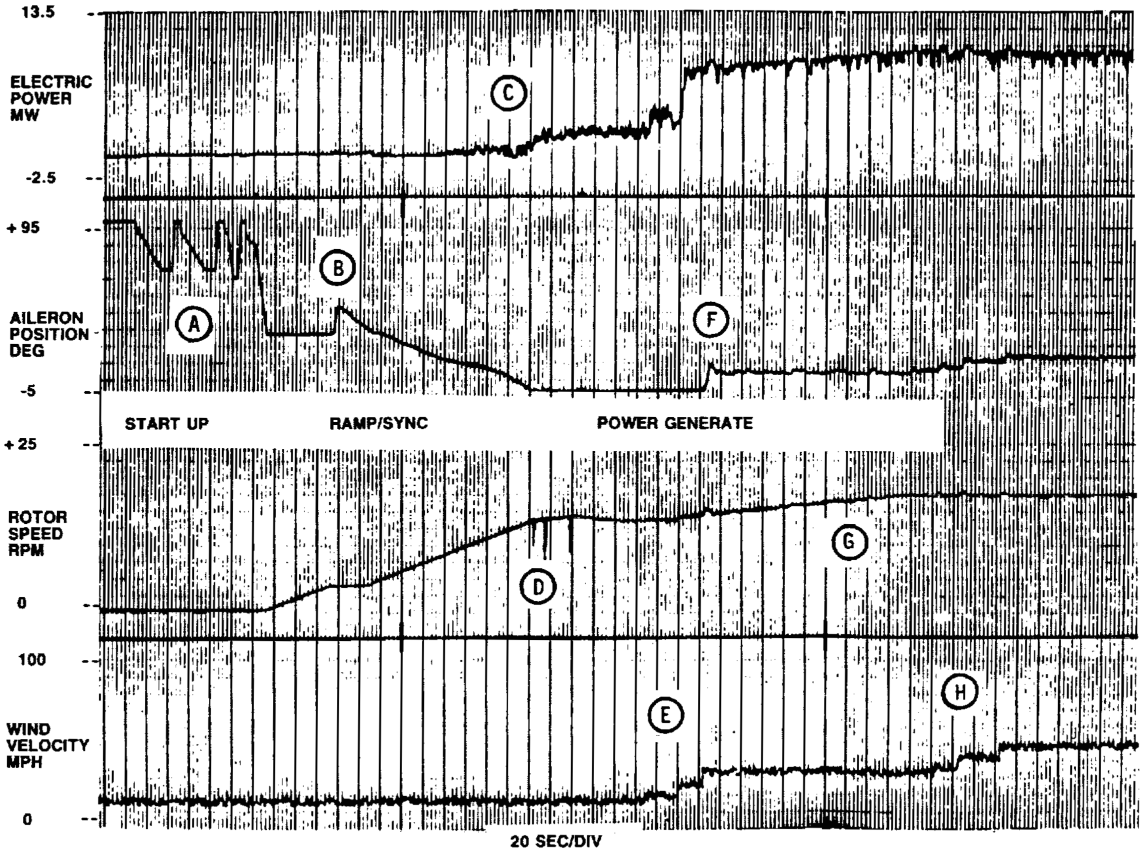

Figure 19- Startup Simulation On Development System

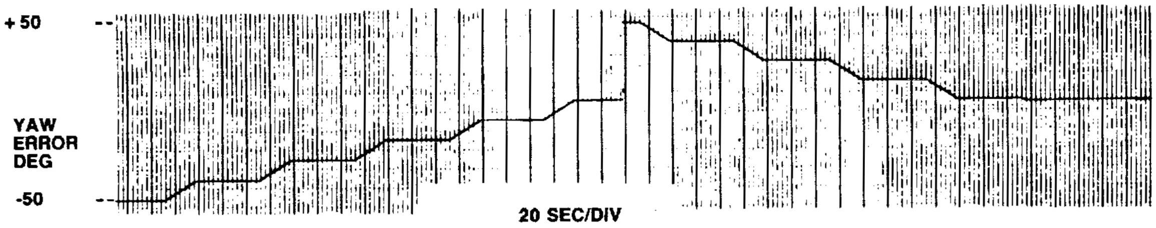

Figure 20- Yaw Drive Simulation On Development System

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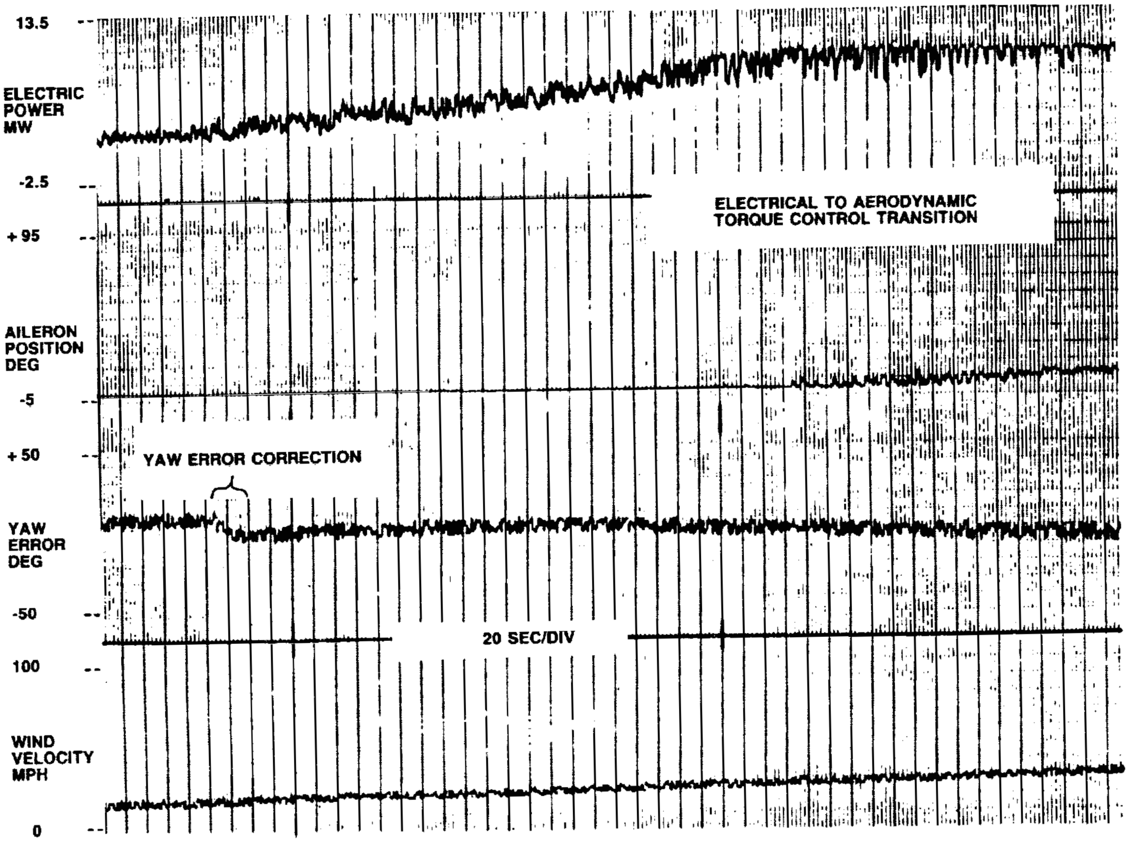

Figure 21- Operating Simulation On Development System