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EXPERIENCE AND ASSESSMENT OF THE DOE/NASA MOD-1 2000 KW WIND TURBINE GENERATOR AT BOONE, NORTH CAROLINA

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ABSTRACT

The borad objectives of the Mod-1 Program are defined including the background information leading to the inception of the Program. Activities on the Mod-1 Program began in 1974 with turbine dedication occurring in July 1979. Rated power generation was accomplished in February 1980. A description of the Mod-1 WT is included. In addition to the steel blade operated on the WT, a composite blade was designed and manufactured. During the early phase of the manufacturing cycle a Mod-1A configuration was designed that identified concepts such as partial span control, a soft tower and upwind teetered rotors that have been incorporated in second and third generation industry designs.

The Mod-1 electrical system performed as designed with voltage flicker characteristics within acceptable utility limits. Power output versus wind speed has equaled or exceeded design predictions. The WT control system was operated successfully at the site and remotely from the BREMC dispatcher's office in Lenoir, North Carolina. During WT operations, TV interference was experienced by the local residents. As a consequence, WT operations were restricted. Although not implemented, two potential solutions were identified. In addition to TV interference, a few local residents complained about objectional sound particularly the "thump" as the blade passed behind the tower. To eliminate the residents' objections, the sound generation level was reduced by 10 db by reducing the rotor speed from 35 rpm to 23 rpm. During January 1981, bolts in the drive train fractured. A solution has been identified but not implemented as yet. During the past two years the public reaction has been overwhelmingly favorable toward the Mod-1 WT Program. This includes the vast majority of local Boone residents.

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1.0 OBJECTIVE

The overall objective of the 2,000 kW Mod-1 Project was to obtain early operational and performance data that could be used in the design of second generation cost-competitive wind turbines. The Mod-1 Wind Turbine was the first megawatt sized machine in the Federal Wind Energy Program to produce electrical power from wind energy. Specific project objectives were as follows:

- Operational and performance data for a Megawatt sized wind turbine in a utility operated application
- Demonstration of unattended, fail-safe operation
- Involvement of utility as user and operator
- Identification of maintenance requirements for large wind turbines

- Involvement of industry in the design, fabrication and installation of a the wind turbine
- Identify components/subsystem modifications to reduce cost, improve reliability and increase performance
- Assess public reaction/acceptance of large wind turbines
- Demonstrate compatibility with utility requirements

A very significant benefit of the Mod-1 Project was the discovery under some conditions that the wind turbine emitted an objectionable sound level to 10 families in the vicinity of the site. Methods to characterize the sound in order to establish acceptable sound standards and to reduce the sound levels became a significant part of the Mod-1 Program.

2.0 BACKGROUND

The Federal Wind Energy Program administered by the Department of Energy (DOE) has as one of its goals the development of the technology for practical cost-competitive wind turbines that can be used to supply significant amounts of electrical energy. As a part of the wind turbine development, the Lewis Research Center (LeRC) of the National Aeronautics and Space Administration (NASA) had the responsibility to carry out the Mod-1 Program. The General Electric Company (GE) under contract to LeRC, designed, built, and installed the Mod-1 Wind Turbine at Howard's Knob (Boone), North Carolina. Blue Ridge Electric Membership Corporation (BREMC), a rural cooperative with headquarters in Lenoir, North Carolina, received the power generated by the Mod-1 Wind Turbine; and BREMC operated the wind turbine remotely from the dispatcher's office in Lenoir.

3.0 CHRONOLOGY

Major project events are shown in the chronology listed below.

Project Initiated	1974
Contract placed with General Electric Co.	July 1976
First Rotation Accomplished	May 1979
Turbine Dedicated	July 1979
Turbine Synchronized with BREMC Network	September 1979
Began Semiregular Operation	October 1979
Turbine Completed Acceptance Testing	January 1980
Utility Training Completed	February 1980
Machine Generated Full Power - 2,000 kW	February 1980
Reduced Rotor RPM Modification Completed	November 1980
Machine Developed Drive Train Problem	January 1981

4.0 MACHINE DESCRIPTION

4.1 CURRENT MOD-1 WIND TURBINE GENERATOR

The Mod-1 2000-kW wind turbine generator is mounted on top of a truss tower with its horizontal rotor axis 140 feet high. Its two blades are 200 feet in diameter (fig. 4.1-1) and located downwind of the tower. The nacelle/bedplate, which supports and encloses all equipment mounted on top of the tower, is driven through a yaw-bearing assembly that rotates about the vertical axis of the tower in response to changes in the wind direction. The tower is 12 feet square at the top and 48 feet square at the bottom and is anchored to reinforced concrete footings at each leg. Figure 4.1-2 shows the machine installed on Howard's Knob, at Boone, North Carolina. The elevation at the site is approximately 4500 feet above sea level. The original design specifications are presented in table 4.1-1.

The wind turbine assembly consists of the rotor assembly, the drive-train/bedplate assembly, the yaw assembly, and the tower (fig. 4.1-3). The turbine rotor initially operated at 35 rpm and generated 2000 kW of electric power in a 25.5-mph wind (at 30 ft.), and was modified to 23 rpm and 1350 kW in November 1980. The hub and blades are connected to a low-speed shaft that drives a gearbox. In the gearbox the shaft speed is increased from 35 rpm to 1800 rpm and later 23 rpm to 1200 rpm. A high-speed shaft connects the gearbox to the alternator. The entire system weighs 655,000 lb, 335,000 lb machine weight and 320,000 lb tower weight. Table 4.1-2 presents a weight breakdown of the machine. The major components are described in the following subsections.

Rotor Assembly

The rotor assembly consists of three major subassemblies, the blades, the hub assembly, and the pitch-change mechanism. Each blade is attached to the hub through a three-row, cylindrical roller bearing that permits the full pitch of the blade from the power position (0^o) to the feather position (90^o). Blade pitch is controlled by hydraulic actuators operating through a mechanical linkage with sufficient capacity to feather the blades at an average rate of 8 degrees per second.

The blades are constructed of a monocoque, welded-steel leading-edge spar and an aerodynamically contoured, polyurethane foam afterbody with bonded 301 stainless-steel skins (fig. 4.1-4). Measuring 100.8 feet long with a tapered planform and thickness, the blade uses an NACA 44XX series airfoil with a thickness ratio varying from 20 percent at the tip to 33 percent at the root. The blades, which weigh approximately 21,500 lb each, are assembled in six main sections. Spar welds are located at five stations, as are the trailing-edge-section splices. A transition piece is welded to the spar to provide the blade continuity to the interface with the hub. A longitudinal stiffner and chordwise webs are welded in the spar to provide buckling strength. Ballast weights are used at each blade tip for static and dynamic balance.

The hub assembly consists of a hub barrel and a hub tailshaft (fig. 4.1-5). The hub barrel houses the pitch-change bearing and supports the blades at a 9° cone angle. The tailshaft joins the barrel with a 120° saddle flange and a transition to the circular main-bearing seat and flange. The main rotor bearing is shrink fitted to the hub tailshaft and bolted to the bedplate adapter to form the rotor-bedplate interface.

The pitch-change mechanism positions the blades in response to commands from the control system. It consists of hydraulic actuators, swing links, a thrust ring and bearing, and two blade pitch rods (fig. 4.1-6). The stationary hydraulic actuators translate fore and aft motion to the rotating (35 rpm) pitch assembly through a thrust ring. This assembly is supported by both stationary and rotating swing link arms to maintain clearance from the low-speed shaft and thus allow the fore and aft motion to change the pitch of the blade through the pitch rods.

Drive Train/Bedplate Assembly

The drive-train assembly consists of a low-speed shaft and couplings, a three-stage gearbox, and a high-speed shaft that drives the alternator (fig. 4.1-7). The high-speed shaft incorporates a dry-disk slip clutch for protection against torque overloads and a disk brake that will stop the rotor in the event of an overspeed condition and also is used to hold the rotor in a parked position. The entire assembly is supported on a bedplate and enclosed in an aluminum nacelle fairing for protection.

Yaw Drive Assembly

Yaw rotation of the machine to align with the wind is provided by the yaw drive, which consists of upper and lower structures, a cross roller bearing, dual hydraulic drive motors, and six hydraulic brakes (fig. 4.1-8). Each yaw motor drives a pinion meshing with a ring gear on the inner race of the yaw bearing. The yaw brakes dampen dynamic excitations in yaw motions while the nacelle is being driven. These components are housed in a yaw structure that interfaces between the machine and the pintle structure of the tower.

Tower

The steel tubular truss tower (fig. 4.1-1) is made of seven vertical bays with the bracing designed for bolted field assembly. Tubular members were used to reduce "tower shadow" loads on the blades as they pass the tower. The tower was designed to provide stiffness in the lateral and torsional modes. The bending frequency is 2.8 times the rotor operating frequency, and the torsion frequency is 6.5 times the rotor operating frequency. The maximum design wind load is 150 mph. All the members of the tower were fabricated from A333 steel, which provides good low-temperature fracture toughness.

The tower is supported by separate foundations for each of its four legs. Because of the dead weight of the wind turbine, relatively small tension loads are developed in the foundation. Each leg is secured by eight 1.5-inch-diameter anchor bolts, hooked at a depth of 30 inches into the foundation. Tower baseplate shear loads react through a nonshrink grout to a lip on the foundation that is tied into reinforcing bars in the foundation.

Control System

The control system for the WT includes a PDP Digital Equipment Corporation 11/34 computer located in the ground enclosure at the base of the tower. The PDP 11/34 interfaces with two PDP 11/04 micro-computers. One PDP 11/04 is located in the control enclosure, and the other in the nacelle. The control system provides unattended safe and reliable operation of the wind turbine plus features of a data logging system. It will automatically start, operate, and stop the machine, align it with the wind, and provide dispatcher control through a telephone link. In addition, if the control system detects any operation or machine anomaly, the control system is programmed to safely shut the machine down. Figure 4.1-9 presents a simplified control schematic. References 2 to 4 provide a detailed description and a summary of the design calculations, including an analysis of failure modes and effects.

4.2 KAMAN - COMPOSITE BLADES

Two composite rotor blades, designed and built specifically for operation on the Mod-1 wind turbine by Kaman Aerospace Corporation, Bloomfield, Connecticut, have recently been completed. These blades were developed as the second phase in NASA's on-going evaluation of the applicability of composite construction for very large wind turbine blades. The first phase served to develop the technology for such blades and demonstrated this in a 150 foot test blade, which was completed and static tested in 1978. This was the largest composite rotor blade ever constructed, and successfully demonstrated the potential of this material.

The final blades, illustrated in Figure 4.2-1, are fully compatible with the Mod-1 wind turbine and possess dynamic characteristics equivalent to those of the present steel blades. The blade's main structural member is the D-spar, which reacts all primary loads and comprises over 70% of blade weight. Construction of the spar utilized the Transverse Filament Tape (TFT) process, first used for a rotor blade in the 150 foot blade program. An epoxy resin is utilized for its superior fatigue strength, compatible with the 30 year design life of the blades. The afterbody portion of the blade, a lightweight structure which completes the airfoil cross section, is comprised of upper and lower panel members. These are of sandwich construction, made up of inner and outer fiberglass skins with a honeycomb core of resin-impregnated kraft paper; the panels vary in thickness from 1 inch to 3 inches. An adapter fitting, of welded steel construction, is permanently installed at the inboard spar end, using a bolt attachment. The blades incorporate lightning protection, capable of withstanding 200,000 ampere strokes, and the lightning protection is configured to minimize the adverse effect on the inherently low TV interference characteristics of composites. The new blade also includes an ice detection device, as well as a polyurethane paint system and leading edge protection to withstand environmental effects.

4.3 MOD-1A

Shortly after the completion of the Mod-1 Wind Turbine final design, a trade-off study was initiated on a conceptual design that would take advantage of innovative design approaches identified during the Mod-1 design experience, but could not be incorporated in th Mod-1 due to schedule and cost constraints. This design concept was identified as Mod-1A, and had as its basic objectives the reduction in weight from 327 to 200 tons and the cost of energy from 18 to 5¢/kW-hr (1978-$), see Figure 4.3-1. In the trade-off study, three candidate systems were identified as shown in Figure 4.3-2.

Configuration 3 was selected which has as its major characteristics a teetered hub, two upwind blades with partial span control, an integral parallel shaft gearbox structure, an inclined rotor axis and a "soft" shell tower. The Mod-1A overall outline is shown in Figure 4.3-3. A view of the upper portion of the tower and nacelle is shown in Figure 4.3-4. Although the Mod-1A was not built, many of the concepts identified in this trade-off study have been incorporated in second and third generation designs.

5.1 IMPACT OF POWER GENERATION OF UTILITY GRID

WT Power Generation System

The Mod-1 Wind Turbine (WT) power generation system is shown in Figure 5.1-1. It consists of a synchronous generator, contactor, and stepup transformer with auxiliary power connections on the line side of the contactor. High resistance grounding is provided for the generator to limit ground fault current levels. The contactor is unfused 5 KV class motor starter with a latching circuit breaker type mechanism. Its 50 MVA interrupting rating is more than needed to clear faults fed by either the generator or the utility system. The stepup transformer is Delta connected at 4.16 KV with a generator WYE connection. At the 12.47 KV utility side, the WYE connection is solidly neutral grounded and has lightning arrestors and a fused load break switch for disconnect and protection of the transformer.

The generator has two controls on its output; real power and excitation. Real power is controlled at the turbine rotor via full span blade pitch control and excitation is controlled through a voltage regulator and auxiliary equipment feeding the generator shaft-mounted brushless exciter. Power control is inactive for wind speeds below rated wind speed and the Mod-1 output will fluctuate with wind speed and deliver as much power as it can extract from the wind. For wind speeds above rated wind speed, the controller regulates average power output to the level of the system torque rating with an integral plus lag power error type feedback control. The excitation system controls voltage prior to synchronization with the grid. Voltage, power factor, or reactive power control modes may be selected after synchronization. Most operation has been in reactive power control mode with a 250 KVAR delivery to the grid. A stabilizer circuit is also utilized to modulate the excitation in response to hub speed fluctuation.

BREMC System Description

The Blue Ridge Electric Membership Corporation (BREMC) 12.47 KV distribution system around Boone, N.C. is shown in Figure 5.1-2. The Mod-1 Wind Turbine is connected to the Howard's Knob Circuit, one of three radial feeders from the Boone Substation. Other connections are possible with manual switching, to feed the Sherwood or Hound Ears substations. The effective impedance seen by the WT generator to an infinite bus equivalent is 0.142 per unit on the originally installed generator base of 2 MVA.

The Boone substation has a 12.47 KV bus voltage regulator and a recloser on each feeder. A voltage blocking device was added to the Howard's Knob circuit recloser to prevent non-synchronous reclosing with the WT generator. The substation transformer rating was raised from 6 MVA to 7.5 MVA in October, 1980, by BREMC and has had a 45 minute peak load of 8.1 MVA recorded in 1981. About 3600 customer accounts are served by the Boone substation of which 660 are on the Howard's Knob circuit. A residence located 1400 ft. from WT is the closest load. The most voltage critical load is a water filter plant with 350 total motor horsepower and 67 percent undervoltage dropout on the circuit breaker. The Bamboo circuit, connected to the Boone 12.47 KV bus, has about 1370 accounts, including a hospital and motor loads at a sewage treatment plant.

Utility Requirements

Maintaining constant voltage, service and protecting equipment from faults are the primary operating goals of BREMC. BREMC operation maintains voltage within a 5% band by use of regulators and other devices and limits the size of customer motors that can be full-voltage started. A standard voltage flicker chart, shown in Figure 5.1-3, is appropriate for dynamic voltage fluctuations that are acceptable to most utilities with negligible complaints. The utility grid acts as a large source/sink at constant frequency relative to the WT, and large power fluctuations in the connecting line are not objectionable to the utility as long as they do not cause objectionable voltage fluctuations in the line.

General Operating Experience

BREMC has received no complaints associated with Mod-1 power or voltage disturbances. To quantify the voltage characteristics on the BREMC system, voltage recorders were temporarily installed by BREMC on the 12.47 KV line at the Boone substation and on a circuit supplying power to the meteorological tower which is about 200 feet from the Mod-1 WT. Typical traces from these recorders are shown in Figures 5.1-4a and 5.1-4b respectively.

Figure 5.1-4c shows the line-to-line voltage and phase current at the generator during a transient (breaker closure followed by breaker opening) that occurred during the same period that voltage was recorded at the Boone substation and at the meteorological tower circuit. Although the site voltage fluctuation was almost 7%, the voltage variation at the Boone substation was not discernable on the recorder traces. Most of the recorder voltage change is due to voltage regulator action at the substation, rather than wind turbine produced excitation.

A typical site record of operation at 35 RPM is shown in Figure 5.1-5a. There is a time scale change part way through the record that increases the chart speed by 5 times for better high frequency detail. The power set point was 1000 kW during this time and during the first 60 seconds, the pitch angle is off the electronically controlled stop at about 1.5 degrees in order to regulate. For the balance of the record pitch angle was constant. Power trace oscillation represents wind fluctuations plus drive train natural frequency intermittent oscillation, and 2 per rev response due to tower shadow.

The blade flap bending trace shows the impulsive tower shadow response that occurs once per revolution per blade for the Mod-1 downwind configuration. Voltage fluctuation is limited to $\pm 1\%$ with frequencies 2 per rev and 1 per rev as a result of the power system stabilizer circuit (speed sensor, voltage regulator). The drivetrain fundamental mode damping is increased by the power system stabilizer action and the resulting voltage fluctuation is well within acceptable limits. The reactive power trace (Figure 5.1-5b) is similar to the voltage trace and was delivering an average 65 KVAR (lagging) to the BREMC system.

The amplitude of 2 per rev (figure 5.1-5a) on the real power trace is about 15% peak to peak which is better than the design value based upon the system dynamic simulations made during the design phase. The on-line behavior of the Mod-1 electrical power system at 35 RPM showed no evidence of instability and exhibited adequate well damped decay in transient wind induced oscillations at the drive train fundamental frequency.

A typical site record of power parameters from recent operation at 23 RPM is shown in Figure 5.1-6. The voltage trace, at the generator bus, varies about 4% overall due to the generator power angle changes resulting from drivetrain oscillation with a less than optimum power system stabilizer circuit. A generator bus variation of 4% corresponds to a critical bus variation of 2.2% which is well within the small gust flicker criteria. Reactive power oscillates about ±50 KVAR around the 250 KVAR nominal set point due to drivetrain oscillations also.

The real power and rotor shaft torque traces are in phase which illustrates that drivetrain oscillations are at the torsional fundamental frequency. The frequency of the higher amplitude oscillations is 0.42 hertz, which is near the one per rev frequency of 0.383 hertz. Response at 2 per rev, 0.77 hertz, is also seen at lower amplitude periodically. Shifts in average power at lower frequency are due to wind speed changes or blade pitch changes. Some oscillatory behavior only occurred at 23 RPM with the present control system.

Assessment

The Mod-1 Wind Turbine's electrical generation system has performed as expected on the BREMC system. Voltage flicker characteristics are within typical utility limits. Power variation at 35 RPM is about 15% peak to peak and is of no concern to the user utility. Power oscillations result primarily from the 2 per rev response to tower shadow. Electrical performance showed no evidence of instability and exhibited an adequate well damped response to transient wind induced oscillations. At 23 RPM, oscillatory behavior at the drive train fundamental frequency is higher than at 35 RPM.

5.2 CONTROLS AND UNATTENDED OPERATION

Modes of Operation

The Mod-1 WT was designed to operate in three control modes which are (1) Manual Operation, (2) Automatic Operation and (3) Unattended Operation with Remote Control. The first mode, Manual Operation, enables the on-site WT operator to perform specified maneuvers to perform maintenance and test functions while off line. Included in these maneuvers are (1) orientation of the nacelle at any yaw angle (angle relative to WT vertical axis), (2) orientation of the blades at any angle relative to the hub axis of rotation, (3) orientation of the blade at any pitch angle and (4) rotation of the WT off line at any speed up to and including rated speed. A complete list of functions are shown in Table 5.2-1.

The second mode of operation, Automatic Operation, enables the WT operator at site to start up, set the output power level, obtain data and shut down the WT. All other control functions are performed automatically without operator intervention. The purpose of this mode is to generate power to the utility grid controlled by an operator located at the WT site. If the wind conditions are within cut-in (V_{CI}) and cut out (V_{CO}) wind velocity, the WT will generate power at the operator prescribed set point (or less depending upon the wind velocity conditions) in a fully automatic manner.

The third and last control mode is Unattended Operation/Remote Control which enables the operator located at a remote site to start up, set the power output level, and shut down the WT. The purpose of the mode is to operate the WT from the utility dispatcher's office at Lenoir, N.C. 30 miles from the site with no operators at the WT site.

Control System Description

To understand how the WT operates in the manual mode and the automatic modes (controlled from the site or a remote location) a description of the overall control system is appropriate at this time. The primary control mechanism of the Mod-1 WT is blade pitch control. Off line the primary control parameter is rotor speed, and on line it is generator power. In general the control system performs all sensing, recording, utility communication, signal conditioning and buffering, and command functions for the WT. A block diagram that illustrates the overall functional arrangement of the equipment to perform the control functions is shown in Figure 5.2-1. The upper block of equipment is located in the nacelle and the two lower blocks are located in the control enclosure. The WT system provides precision analog control of blade angle and yaw orientation in response to wind direction, wind speed, power set point, rotor speed and other operational parameters. The control of most functions is dependent upon multiple inputs and varying "logic" within an operation mode. The Control and Recording Unit (CRU), with its data gathering and processing capability, is the system master controller. CRU logic is used to determine whether to operate depending upon operator commands and control parameters. As an example, the operational envelope of wind speed versus yaw error (difference between nacelle direction and wind direction) is shown in Figure 5.2-2. Manual control is also processed through the CRU with inputs from a keyboard to eliminate human control errors and thus provide maximum machine and personnel safety.

Output power level is controlled by commands to the analog pitch control loop in the Servo Controller. This permits considerable flexibility in operation. A discrete power level can be maintained, the system can track wind speed and maximize power output continuously, and the CRU logic enables the system to come on-line automatically and autonomously when wind conditions permit. Also the control system provides maximum energy capture capability at below rated wind speeds, and maintains safe control of rotor speed at above rated wind speeds. Sufficient diagnostic data can be automatically recorded so that the cause of shutdowns or anomalous operation can be readily determined. Operating procedures on the Mod-1 Project require that diagnostic data always be automatically recorded.

The control system has the following specific functions:

1. Control the rotor blade pitch angle to startup, supply sub-rated power at wind speeds between 11 and 25.5 MPH and rated power at wind speeds between 25.5 and 35 MPH (nominal).

2. Control the nacelle position through the yaw drive and yaw brake actuators.

3. Condition, buffer, and optionally record sensor signals.

4. Provide operator interface.

5. Provide remote dispatcher control via telephone line.

6. Provide supervisory, alarm, and shutdown control logic.

These functions are performed fully automatically without an operator in attendance at the site to accommodate internal system variables as well as external variables such as wind speed and direction. A detail set of control system functions during startup and generation are shown in Table 5.2-2.

As stated previously, control of blade pitch angle is the predominant dynamic function which directly controls rotor torque. A detail listing of pitch control modes required to operate the WTG with associated operating conditions is shown in Table 5.2-3. The startup sequence to synchronize with the utility grid is shown in Figure 5.2-3.

The second control function positions and holds the nacelle by actuating the hydraulic yaw motors and the yaw brakes. To be able to collect the maximum wind energy possible, the nacelle must be rotated about its vertical axis and aligned with the wind direction. Control logic for the four wind speed regimes is given in Table 5.2-4. If the average yaw error has persisted above five degrees for five minutes, the yaw hydraulic motors are turned on, in the appropriate direction, until the corrected angle is less than one degree. Because of the slow 1/4 degree per second yaw rate, a shorter persistence period is selected as the yaw error increases, as shown in Figure 5.2-4. This change in sensitivity allows higher energy capture during a changing wind direction.

The WT is a complex electromechanical system that must be protected from internal failures and external forces such as wind, ice, snow and temperature extremes. For this reason, fail safe logic has been designed into the WTG controls. The types of shutdowns and the criteria for each shutdown are shown in Table 5.2-5. Backup direct acting sensors are also provided for overspeed control of the emergency feather and brake systems.

Experience

One of the main objectives of the Mod-1 Program was the demonstration of the feasibility of remote utility wind turbine control. Communication for remote operation is accomplished at 300 baud via Southern Bell Co. telephone lines. Initial remote control occurred during acceptance testing in February 1980 and was regularly used thereafter when the WT was not allocated to sound and TV interference testing or undergoing major modifications. The majority of the remote control operation occurred between 11:30 PM and 8:00 AM. After remote control operation procedures were established, phone line communications were found to be acceptable. Several dispatchers at BREMC were trained and operated the WT successfully. As experience was gained, additional machine operational parameters were made available to the remote operator to provide a more thorough understanding of the machine operating state. Typical learning problems were experienced including remote terminal hardware failures, occasional switch adjustments and lack of initial operator familiarity with control procedures. Since the WT control logic was based upon a fail safe philosophy with numerous safety checks, personnel and terminal hardware problems did not result in WT misoperation or malfunction.

Significant and beneficial controls information, data and experience were acquired during the WT operation phase. The most significant problem in the WT control system was computer to computer communications. This occurred between the Digital Equipment Corporation (DEC) PDP 11/34 Control and Recording Unit (CRU) and two PDP 11/04's located in the WT Nacelle Multiplexer Unit (NMU) and in the control enclosure Ground Multiplexer Unit (GMU), respectively. The occasional loss of communication between computers resulted in unscheduled WT shutdowns. Operator error message statements such as Nacelle Multiplexer Link Fail, Transmit Buffer Overrun or Connect Fail are printed on the operator terminal when communication failures occur to aid in diagnostic procedures. Communications are controlled by DEC commercial computer electronics boards (DMC-11's) which contain a microprocessor. The kinds of communications failures can be understood by examining the definition of operator error message statements. A Connect Fail occurs when a NMU or GMU fails to return an acknowledgement of an attempt to communicate by the CRU. A Nacelle Multiplexer Link Fail occurs when excessive time for data transfer occurs between either the NMU or the GMU and the CRU. If a successful data transfer occurs, a buffer is released for reuse. When the data transfer is unsuccessful, a buffer is not available for transfer of additional information and a Transmit Buffer Overrun occurs.

Before active investigation and solution implementation began in March 1980 of the "link failure" problem, communication malfunctions were experienced about 8 days per month. As causes were determined and solutions implemented, malfunctions were progressively eliminated by November 1980. The specific steps taken to eliminate computer to computer communication malfunctions were numerous. The initial step in March 1980 was to install slower byte rate microprocessor DMC-11 boards, 50 kilo bytes per second (KBPS), in place of the existing faster DMC-11 microprocessor boards, 1 million bytes per seconds (MBPS), in the control enclosure-nacelle link. The slower byte rate boards are more tolerant of brief communication lapses. As a result these new boards have reduced link failures but did not eliminte them.

Secondly, in April 1980 the allowable cycle time for computer communication was increased to 350 msec from 150 msec. This reduced link failures further, particularly in the automatic mode. To improve the manual mode, the cycle time was increased to 600 msec in May 1980. Subsequent to this modification, link failures consisted primarily of Transmit Buffer Overruns with the preponderance occurring during lightening storms and yaw maneuvers. In spite of several electrical measurements indicating that the yaw slip ring was performing acceptably, an auxiliary cable bypassing the slip ring was installed for diagnostic tests. Since there were no further link failures while the bypass control cable was installed, it was concluded that the last major cause of communication irregularities was due to a deteriorated slip ring. In May 1981 a slip ring manufacturer's inspection revealed salt deposits on the sliver plated contacts. This was the second such occurrence of salt deposit detection on the slip ring contacts even though prescribed cleaning procedures were used about 22 months earlier. Based on the pattern of link failures, it was concluded that the slip rings were progressively being contaminated with a salt deposit. Since the Mod-1 WT is not in a salt air climate, it is speculated that some fluids used in WT operation or maintenance such as hydrualic fluid, may contain a salt additive and might have inadvertently spilled into the slip ring assembly during the initial assembly period. It is planned to investigate the chemical composition of all Mod-1 fluids to confirm this hypothesis. No link failures have occurred with the control system since the May cleaning that can be attributed to the yaw slip ring.

Another lesson learned was the need for qualified and readily available expertise for the computer system preventative and corrective maintenance. Mod-1 site operation records indicate that for the period March - December, 1980 that expert computer technicians were required 13 times. Only during July and August was no preventative and corrective maintenance required. In addition to preventative maintenance every three months, computer services were needed for repair of the line printer, replacement of electronic boards, replacement of disk drive, tape unit repair and remote terminal repair. On call maintenance service was purchased from DEC since they supplied the total computer system including peripherals.

Operation with a mini-computer based control system proved to be highly flexible in making system changes quickly and inexpensively. As an example, after it was concluded that the system rotor speed had to be slowed to reduce the sound generation to acceptable levels, the Central Processor logic within the CRU was easily modified to operate the WT at 23 RPM with a 1200 RPM generator. The control system flexibility was further demonstrated when the WT was operated at 23 RPM with existing 1800 RPM generator (prior to a generator change) while generating power to a temporary load bank without changing control hardware.

Also during routine test, tne CRU data base was temporarily changed numerous times in minutes to suit test requirements. Finally, since the Mod-1 WT was the first development vehicle planned to demonstrate the feasibility of a large megawatt WT, a number of unexpected events occurred that required data for analytical investigation. The data archive feature of storing historical operational data on magnetic tape within the Control and Recording Unit proved useful in investigating, analyzing and evaluating all facets of system operation. This system records on tape all "traffic" between the Control and Recording Unit (CRU) and each of the Remote Multiplexer Units (RMU's), all "traffic" between the CRU and BREMC, all communications between the CRU and the on-site operator, and all changes in data states. Recorded data is available for troubleshooting via playback processor when the WTG system is not operating. An RKO 5 disc has been allocated to record operational data for analysis if the magnetic tape recorder is not available.

Assessment

The Mod-1 WT control system should be more appropriately referred to as an operational control, data acquisition, recording and display system. Based upon the WT system performance during and after the program acceptance test, a general assessment is that the control system performed as designed. The WT was operated successfully in all three modes including the unattended/remote control mode from the BREMC dispatchers office in Lenoir, North Carolina about 30 miles from the Howard's Knob WT site. The control system has the capability of a small conventional power plant in terms of memory and processing speed. When compared to 1981 state of the art WT control techniques, the Mod-1 is considered the equivalent to a second generation wind turbine control system. Perhaps the greatest advantage of the Mod-1 control system is flexibility and this was a key requirement of the nation's first megawatt scale research and development Wind Turbine Generator. With the experience gained from the Mod-1 system, second generation machines are using a more simplified and durable microprocessor.

5.3 ENVIRONMENTAL ISSUES

While conducting the initial checkout of the WT during the winter of 79-80, complaints were received from residents in the immediate vicinity that the machine was producing interference with TV reception and was emitting an annoying sound. Machine operations were restricted to minimize these disturbances to the affected areas while evaluation studies were initiated and established experts hired to properly evaluate these environmental issues. It should be noted that only ten households have complained about noise, and 35 households have noted some TV interference out of a community with a population of over 10,000.

The WT is located on top of Howard Knob (elevation 4420 feet), a heavily wooded mountain in the Blue Ridge Chain of the Appalachian Mountains. Howard Knob is located outside the city limits of Boone (elevation 3266 feet), in Watauga County, in northwest North Carolina near the Tennessee border. It is important to realize that the mountainous terrain (see figure 5.3-1, local map of Boone) surrounding the Mod-1 site has a significant influence on how these environmental issues affect the residents in the community.

5.3.1 Introduction of TV Interference

Throughout 1980, TV reception was investigated and evaluated at areas where complaints of TV interference were received and at other locations in the general area to fully identify the scope of the problem. Communications consultants were used to conduct these test programs and investigations. The geographic orientation of the nine TV channels that the Boone residents watch are illustrated in figure 5.3.1-1, and all of the transmitters are over 46 km from the WT. Table 5.3.1-1, entitled "TV Channels Available in Boone" lists the 9 network channels, station locations, network affiliation, effective radiated (visual) powers, transmitting antenna locations, distances from the WT, and compass bearings.

Discussion

The quality of TV reception depends on the signal to noise ratio of the receiver, the receiving antenna used, and the TV signal strength. To determine the quality that is possible in the Boone area, the ambient field strengths were measured at the test sites on all of the available TV channels. Since most of the homes are located in the valleys below the top of the surrounding hills, it was expected that the TV signals would be weak due to shadowing by the terrain. This proved to be the case; and according to the industry specification of the signals needed for high quality service (good reception), the reception of most channels at almost all homes would be classified as poor. The severity of wind turbine interference with TV reception depends on the ratio of the WT's scattered signal strength to the ambient signal strength at the location in question. The TV signal strengths were determined at the base of the wind turbine tower and at the top of the nacelle approximately 150 ft. above the ground. The signal strengths were similar at the nacelle and base of the wind turbine, and the signals received on all channels were quite strong. Because the signal strengths are so strong at the site of the Mod-1 the reflected signal throughout the interference regions will have a large potential for causing TV interference.

The blades of a wind turbine can interfere with TV reception by producing video distortion. No audio distortion has been observed. When the wind turbine is operating, the interference is caused by the time-varying amplitude modulation of the received signal produced by the rotating blades. In the neighborhood of a wind turbine, the signals scattered by the blades combine with the primary broadcast signal to create a form of time-varying multipath signal, thereby amplitude modulating the total received signal. The modulation waveforms consist of sync pulses, and since each blade of the WT contributes independently, the pulses repeat at twice the rotational frequency of the machine rotor. If sufficiently strong, these extraneous pulses can distort the received picture. When the blades are stationary, the scattered signal may appear on the TV screen as a ghost whose position (separation) depends on the difference between the time delays of the primary and scattered signals. A rotation of the blades then causes the ghost to fluctuate which can result in a more objectonable picture. In such cases, the received picture displays a horizontal jitter in synchronism with the blade rotation. As the interference increases, the entire fuzzy picture shows a pulsed brightening and still larger intereference can disrupt the TV receiver's vertical sync causing the picture to roll over (flip) or even break up. This type of interference occurs when the interferring signal reaches the receiver as a result of scattering off the broad face of a blade and is called backward region interference. In the forward scattering region, when the wind turbine is almost in line between the transmitter and the receiver, there is virtually no difference in the times of arrival of the primary and secondary signals. See figure 5.3.1-2 for layout of forward and backward scatter regions. The ghost is then superimposed on the undistorted picture and the video interference appears as an intensity (brightness) fluctuation of the picture in synchronism with the blade rotation. In all cases the amount of interference depends on the strength of the scattered signals relative to the primary one, and the interference decreases with increasing distance from the wind turbine. Interference decreases with increasing distance from the machine, but in the worst cases can still produce objectionable video distortion at distances up to a few kilometers. At a given distance from the wind turbine, the interference increases with increasing frequency; and the interference is worse on the upper VHF channels.

Test Results and Tentative Solutions

As a result of the measured data and the analysis performed by the University of Michigan, Department of Electrical Engineering [6, 7], the following observations were made:

1. In the city of Boone and the surrounding area, the ambient field strengths are low on all of the available TV channels. Even

with the WT stationary, the quality of reception is poor; and a high performance antenna is not sufficient to make it good.

2. With the WT operating, varying amounts of TV interference were found at all test areas and on all of the TV channels. One reason for this is the large increase in reflected field strength in the test area due to the Mod-1 wind turbine. With a high performance antenna, the backward region interference observed at the test areas was judged to be acceptable; while in the forward region, the interference was judged to be unacceptable.

The four tentative solutions to the Mod-1 TV interference problem were considered as follows:

1. Restrict machine operating time to avoid operating during prime TV time.

2. Use special high performance antennas at the affected residences.

3. Extend cable TV into affected areas.

4. Rebroadcast television signals via television translators to the affected areas.

Restricted machine operation to avoid prime time television was implemented early in 1980 to minimize the inconvenience of the Boone residents. This was considered only a temporary solution and for the long term would not be economically advantageous. High performance antennas would be economically attractive but would not completely solve the problem. They would eliminate interference in the backward interference region but would be totally ineffective in the forward interference region. The city of Boone and the densely populated areas around the city have access to cable TV. Cable service has not been extended to all the valleys and mountainous areas surrounding Boone and the Howard's Knob area because it is not attractive from a business point of view. These were the areas where the WT caused the TV interference problems.

John F. X. Browne and Associates made an in-depth investigation on the use of TV translators as a potential solution in the Boone area. A TV translator is a rebroadcast station operating with a low power transmitter, usually 10 to 100 watts. The translator converts the conventional VHF TV signals to specific UHF TV channels and rebroadcasts the signals to a specific area. The translator approach depends upon the interrelationship of many variables which include: (1) terrain, (2) power, (3) antenna height, pattern, (4) operating frequency, (5) viewers' reception facilities and (6) localized objects such as buildings and trees which restrict reception. The TV signal quality, within the affected area adjacent to the WT site, provided by the translator system would be equivalent to that provided by a high power TV station in a metropolitan area. These broadcast stations are considered to be a "secondary" service by the FCC and are licensed on the basis of non-interference with regular TV broadcast stations.

Summary

Cable TV and rebroadcast via translators both would provide technically adequate solutions to eliminate television interference in the affected areas surrounding the Mod-1 Wind Turbine on Howard's Knob. Special antennas will not solve the TV problem associated with wind turbines. Restricting the operating time for a wind turbine is not considered an acceptable solution to TV interference.

5.3.2 Sound

Introduction

During the initial checkout operation of the WT in the Fall of 1979, a few complaints were received from local residents that the machine was emitting an objectionable sound. In some instances, it was reported that the sound was accompanied by vibration of residential houses. The character of the sound was described by affected residents as an audible "thump" (similar to a large heart beat) at a repetition rate equal to twice the blade rotational speed. The "thump" occurs when a blade passes behind the tower. In addition to the thump, a typical WT "swishing" sound can be heard in the background that is relatively inconspicuous.

Initial complaints were sporadic and as a consequence difficult to correlate. This inconsistent pattern of complaints was partially due to the seasonal nature of the Boone residential community in the vicinity of the WT. To date ten specific residences within a 2 mile radius have complained about objectionable sound with only two residents complaining persistently. The residents complaining about objectionable sound also complained about TV interference previously described in Section 5.3.1.

As a result of the sound complaints, a joint NASA/BREMC/GE decision was made to limit operation of the WT to daylight hours with the exception of brief periods during the night for necessary sound measurements. To gain community understanding, BREMC conducted informative meetings with affected residents in March of 1980. At that time consideration of a rotor slow down to 23 RPM later in the year was mentioned as a potential method to reduce sound levels. Also during 1980 BREMC released articles to the local press informing the general public of the status of the sound situation.

Testing Program and Results

During the early winter of 1979 the Solar Energy Research Institute (SERI) conducted a limited sound survey at the wind turbine site and near a few affected residences. This survey confirmed the existence of random sound levels at the residences that could be considered the basis for complaints. This is especially true for a rural community that has a very low level of background sound. The initial measurements also revealed that additional in-depth tests would be required to obtain a basic understanding of the sound generation and propagation mechanisms. Initial concerns in addition to the basic sound level were low frequency sound and structural vibration. At this time local atmospheric and terrain characteristics were suspected of intensifying sound at some locations.

The first in a series of three in-depth sound measurement and analysis programs was conducted during February, March and April of 1980. This program was implemented by GE and SERI, and consisted of sound pressure level measurements versus time and frequency. These measurements were made at the WT and in and near the home of a resident that had registered sound complaints on several occations. In addition to sound measurements, vibration levels in the home of one resident were measured. To evaluate the meteorological effects on sound propagation, Penn State University and the University of Virginia personnel measured atmospheric parameters of temperature and wind velocity as a function of elevation.

The results and basic data from this test program were documented in a report entitled Mod-1 Wind Turbine Generator Preliminary Noise Evaluation[9]. Test data indicated that objectionable sound was basically a sequence of impulses at a blade-passing the tower repetition rate as shown typically in Figure 5.3.2-1. A typical sound pressure level versus frequency curve is shown in Figure 5.3.2-2 as measured within 50' of the WT when generating 1000 kW on February 12, 1980. A comparison of the sound pressure level outside the house of a local resident versus inside the house can be obtained by comparing Figures 5.3.2-3 and 5.3.2-4.

It was concluded from this initial test program that the frequency range of primary interest with regard to complaints was from 5 - 70 Hz. The condition referred to as a "thump" is characterized by an increase in sound especially in the 20 - 30 Hz range. Any objectionable house vibration is due to low frequency acoustic energy in the same frequency range (20-30 Hz). A mathematical model was developed as a sound level predictive tool which suggested that appreciable atmospheric focusing of sound energy could be typical of the Howard's Knob area. Finally, it was predicted that a reduction in rotor speed from 35 RPM to 23 RPM would reduce sound; however, the amount of sound reduction might be marginal with respect to complaints because affected families had been sensitized.

The second series, in the sound measurement program, was conducted with the WT in a temporary configuration operating at 23 RPM generating power into a portable resistor type load bank. The results indicated an average 8 - 10 db reduction in sound power level when compared to the 35 RPM sound power levels, see Figure 5.3.2-5.

These measurements supplied supporting data to continue with the program plan to reduce the WT rotor speed to 23 RPM by replacing the 1800 RPM synchronous generator with a 1200 RPM generator.

The third series in the sound measurement program was conducted in January 1981 after the 1200 RPM generator installation when the WT was generating power into the utility grid at 23 RPM. Statistical data was recorded in the 31.5 Hz octave band near field (approximately 240 - 270 feet from the WT center) at three locations and in the far field at two of the local residences. Data was recorded continuously and statistical distributions were automatically generated for half hour periods so that sound pressure level data could be plotted versus the percentage of the time that a specific level occurred. A typical curve is shown in Figure 5.3.2-6 with a 50 percentile near field (at the WT) sound pressure level of 71 db compared to a minimum ambient level of 54 db.

The results of this test program have been reported in a document entitled Mod-1 Wind Turbine Generator Statistical Noise Studies[2] by R. J. Wells of the General Electric Company. At one residential area, the average sound pressure level (50 percentile) varied from 64 db when a complaint was registered to 51 db when no complaints were received, see Figure 5.3.2-7. At the second residential location the average sound level (50 percentile) was 49 db while on-line, see Figure 5.3.2-8.

Based upon the results of this test phase, it can be concluded that the sound level in the 31.5 Hz octave band is a reasonable choice for a convenient measure of wind turbine sound. The sound levels in the near field are essentially constant for a given yaw angle and wind velocity. The sound levels measured in January 1981 correlate closely with the prior 23 RPM load bank tests from the summer of 1980. Much of the time the far field levels in the 31.5 Hz band are about as would be expected based upon the assumption of spherical divergence. No complaints occurred under these conditions. The condition referred to as "thump" seems to be caused by occasional atmospheric focusing due to unusual wind and temperature gradients. At one far field location, measured levels as much as 25 db above that expected by spherical divergence occurred, and in such cases the far field level exceeded the near field level.

Assessment

Complaints about objectionable sound resulting from WT were restricted to an area with a radius of two miles and to 10 residents. Only two of these residents complained persistently. Based upon the concerns of the local Boone residents, WT operation was curtailed during early evening hours with a few exceptions. The character of the sound is repetitive, similar to a heart beat. Reducing the rotor speed to 23 RPM reduced the sound level about 10 db near the WT as predicted. At 23 RPM statistical analysis of sound measurements at the WT indicate that the average sound (50 percentile) was about 70 db and that 1 percent of the time the sound level was about 77 db. Adjacent to one of the local residents who was more persistently annoyed the average sound level was about 52 db, and 1 percent of the time exceeded 60 db for the test period. At the same location during a one hour and half period (1-1/2) when a complaint was received, the average sound level was 63 db and 1% of the time exceeded 77 db. The measured sound levels at local residences which are equal to or greater than sound levels measured at the WT on rare occasions substantiate the notion that atmospheric focusing is a significant factor in causing the limited number of complaints at Boone. Another interrelated factor in causing sound complaints is WT produced TV interference that creates an awareness on the part of a sensitized resident of WT operation via a visual medium.

5.4 Wind Turbine Performance

The performance of the Mod-1 Wind Turbine was originally reported in 1980 in reference [12]. The experimental data used in this performance analysis of Generator Power Output vs. Wind Speed @ the Hub was preliminary at that time, but the machine was operating as predicted. Figure 5.4-1 illustrates the same plot as the above reference except that there are substantially more data samples included in each plotted point. The machine's performance follows the design prediction very well. A few data points from the reference plot and figure 5.4-1 are above the design line indicating that the machine has a higher overall efficiency than was originally predicted.

As expected losses occur in the drive train and rotor of the machine. The generator, bearings and gearbox are standard components and their manufacturers have well documented efficiency curves.

Assessment

The resulting efficiency increase is attributed to a higher than predicted aerodynamic performance of the blades. The original Mod-1 Wind Turbine performance calculations may have been conservative due to the lack of blade aerodynamic performance data particularly with regard to blade surface effects. A more detailed performance analysis of the Mod-1 Wind Turbine has been reported in reference [13].

5.5 DRIVE TRAIN

5.5.1 Drive Train Dynamics

Introduction

In March 1980, trade off studies were initiated to identify near term practical methods of reducing the sound level emitted by the machine. Reducing the rotor speed was selected as the option to be implemented. This change could be accomplished by changing synchronous generators, (1800 RPM to 1200 RPM), thus reducing the rotor speed from 35 to 23 RPM. This option was selected because it yielded the best set of advantages: (1) Minimum changes to the machine; (2) minimum time schedule to complete the machine changes; (3) minimum costs; and (4) high probability of solving the sound problem. A solution had to be selected early to initiate hardware procurement for installation during the fall of 1980 for subsequent testing during the winter of 1980. Selecting the reduced rotor speed option in March 1980 provided six months to procure the hardware and schedule the change.

Discussion

During the analysis and design period for the reduced rotor RPM option, it was realized that the once per rev excitation frequency (0.383 Hz) is close to the drive train natural frequency of 0.41 Hz when operating the WT at 23 RPM. This situation presented the possibility that if the blades were not well balanced or aerodynamically trimmed, an undesirable 1 P response might be experienced in the drive train. The WT was operated at 23 and 35 RPM in a manual mode and synchronized to the utility grid at 35 RPM without any indication of an inbalance between blades. Therefore, since there was not a positive indication of an impending problem associated with this proposed change, it was decided to proceed with the rotor speed reduction.

During the period of time when the WT was operated at 35 RPM, the machine performed well, was compatible with the utility grid, and was dynamically very stable. When the reduced RPM option was completed, our concerns during the analysis and design period became a reality. During gusty wind periods, the machine experienced power swings of ± 40% about the control set point during intermittent time periods. While this did not affect the utility or its customers because of the relative size of the utility and power generated by the wind turbine, power swings of this magnitude are undesirable. Power swings of this magnitude on the WT would reduce the life of some components primarily the gear box, and on commercially produced wind turbines would add unnecessary capital equipment costs to withstand 40% fatigue type overload conditions. To avoid potential damage to the WT gear box, the power set point was temporarily limited to 1,000 KW until the power swings could be reduced.

Wind turbine generators have a lightly damped torsional mode generally below 1Hz which is determined by turbine inertia and shaft stiffness. The generator inertia for the 35 to 23 RPM change increased from 50.5 lb-ft-sec^2 to 69.7 lb-ft-sec^2, which was an insignificant drive train inertia change. Frequency and damping ratio of the first torsional mode are influenced by four factors: (1) drive train; (2) power regulation; (3) power system stabilizer; and (4) hub speed feedback. The first torsional mode of the WT drive train is 0.41 Hz, which primarily represents the movement of the hub and blades against the effective stiffness of the shafting, gearbox, and generator conection to the power system. Since the electrical stiffness between the generator and utility power system is higher than the mechanical stiffness between the rotor and generator, the displacement of the turbine rotor on the first torsional mode is much greater than the displacement of the generator rotor. The stiffness ratio of utility power system to the wind turbine drive train system is 8.33 to 1. Electrical damping at the generator is difficult because the generator rotor is a minor part in the displacement caused by the first torsional mode. Shaft damping can be effective but would require extensive structural changes.

Assessment

Damping at the rotor can be achieved by a more active blade angle control. A control system analysis of a Mod-1 system indicated that increasing damping of the first torsional mode from 5% to 25% of critical damping could be achieved by adding a signal in phase with hub speed deviation to the output of the blade pitch angle controller. This would require a more active pitch hydraulic system which could increase maintenance on this system at some time in the future, since the system was not originally designed for the more active duty cycle associated with the added hub speed control signal.

During January 1981, the WT was operated at the reduced power set point while sound measurements were made to evaluate the machine operating at 23 RPM. The program operating schedule called for completion of the evaluation and demonstration of the 23 RPM control system problem in February 1981. A problem developed in the drive train on January 20, 1981, which terminated operations, which will be discussed in the next section.

5.5.2 Drive Train Problem

Introduction

On January 20, 1981, the WT experienced a failure of 22 studs in the drive train. Specifically these studs attached the low speed shaft gear coupling to the rotor hub. Figure 5.5.2-1 illustrates the general drive train arrangement on the WT and identifies where the bolted joint is located. When the rotor hub separated from the low speed drive shaft and remaining portion of the drive train, the safety system initiated feathering of the blades which stopped the rotor/hub and opened the circuit braker to the utility which electrically isolated the generator from the grid.

Discussion

The machine was safely secured and sustained relatively minor damage during the safety system controlled shutdown. The torque plate which is mounted on the rotor hub assembly contained the 22 broken ends of the studs within helicoil inserts. The remaining portions of the broken studs were recovered from the lower portion of the bedplate. The outer sleeve of the gear coupling was damaged during the shutdown and will require replacement. This shaft coupling outer sleeve rapped the pitch rod adjusting mechanism during the shutdown. These adjustment mechanisms and the "uniball" end fittings must be replaced. The instrumentation and power wiring bundle and conduit within the low speed shaft was severed when the coupling/low-speed shaft separated from the rotor hub and must be replaced.

Figure 5.5.2-2 illustrates a section view of the hub/shaft interface and locates the studs that failed. During assembly personnel access to the backside of the hub torque plate was limited which necessitated the blind connection. Figure 5.5.2-3 illustrates the stud/helicoil installation in the rotor hub torque plate/low speed shaft coupling joint. Self locking stainless steel helicoils inserts were used to increase the thread strength in the mild steel torque plate. The studs pass through clearance oversized holes needed for helicoil installation in the torque plate before engaging the helicoil insert.

The rotor hub torque plate to coupling interface was designed as a conventional friction joint with the fastening studs providing the preloading to a joint capacity of 885,000 ft-lbs. The drive train had a rated torque capacity of 442,000 ft-lbs which yields a joint safety factor of 1.99. The drive train has a slip clutch adjusted to slip at a setting of 829,000 ft-lbs which would slip at 93% of the joint rating.

Metallurgical analysis of the failed studs revealed that high strain; predominantly low cycle bending fatigue was the cause of the stud fractures at the helicoil end. The stud material was found by metallurgical analysis to be of excellent quality and free of any defects. After the failure, examination of engineering log books indicated that the studs were not properly preloaded which is believed to result in a joint torque capacity of 683,000 ft-lbs or only 77% of is original design value. The stud geometry and spacing in the oversized torque plate and gear coupling holes would allow a relative rotation of 1 degree between the torque plate and gear coupling. Torque loading of the drive train forced relative rotation which in turn failed the studs via bending fatigue. A second major contributing factor that the slip clutch malfunctioned on several occasions before it was discovered operating improperly. A third contributing factor was occasional torque loadings in excess of the design values including both peak and cyclic torque overloads. The principal cause of this failure can be attributed to improperly installed studs and a malfunctioning slip clutch which was installed as an overtorque protection device.

Assessment

The failed joint has been fully reviewed and analyzed and a suitable repair method identified. The drive train damage can be repaired for the most part in the nacelle with only the low speed shaft and pitch change mechanism being removed. The rotor hub torque plate rework will require precision machining, and several sources that can provide this type of service have been identified.

Specific Recommendations

Basic friction-torque joints are desirable in future wind turbine applications because they are lower cost than other conventional designs. Also, some drive train designs may have no other alternative than to use friction torque joints. Designers in designing this type of joint should consider providing a friction torque capability for all specified loads with a safety factor of 2.5 as a minimum. In addition, the designer should assume that the joint will slip near limit loads and the fasteners will be carrying the torque load in shear. Clearances around fasteners should be minimized so that the fasteners will be more uniformly loaded. Designers are urged to be conservative in selecting a friction coefficient for this type of joint. Through joint fasteners that are positively locked are recommended, and helicoils should be avoided in this type of joint. Lastly, the fastener tensioning technique must be verified by test and verified at installation by proper inspection. Using a slip clutch as a overtorque safety device in wind turbine is considered acceptable. Particular attention must be paid to the application, installation and understanding all facets of its operation and maintanence. Designers must obtain enough detailed information from the slip clutch manufacturers to fully understand the operation and limits especially if the unit is not a shelf item or a shelf item has been modified.

5.6 PUBLIC REACTION AND ACCEPTANCE

Introduction

Over the past two years, the public reaction has been favorable toward the Mod-1 Wind Turbine Project. This included the vast majority of local people who live in and around Boone near the turbine site. In the regional area of North Carolina and over the rest of the country, people were supportative; but not as interested in the project as the Boone residents. Nationally, the Mod-1 Project was recognized as the first operational megawatt sized wind turbine in the world.

Discussion

There have been many articles in the North Carolina and Boone papers reporting on the various phases of the Mod-1 Project over the past two years. Occasionally, national publications such as Time Magazine, the Wall Street Journal, Aviation Week & Space Technology, have had articles on the Mod-1. Trade journals including 1980 Generation Planbook and Electrical World have published material describing the Mod-1 Wind Turbine. Newspapers outside of North

Carolina such as The New York Times, Washington Post, Cleveland Plain Dealer, and Philadelphia Inquirer and others have published articles about the project. The North Carolina television stations have also reported numerous times on the Mod-1 Program.

Various management personnel from the Blue Ridge Electric Membership Corporation have given an average of over 100 talks per year around the state of North Carolina to various civic, religious, and public organizations during the first two years of the project. The Blue Ridge management has reported that the groups that they have talked to as well as the general Boone residents have been very supportive of wind power as a form of generating electrical energy. The academic community from Appalachian State University, a local college, have been very supportive of wind power by conducting energy seminars including wind energy reviews and are conducting their own wind energy projects which consists of operating a small horizontal axis wind turbine.

The Mod-1 site is a continual attraction to visitors to the Boone area and residents from the southeastern part of the United States. Approximately 4000 per year informational brochures on the Mod-1 have been passed out to site visitors during the normal working hours by maintenance personnel. During the fall of the year when the leaves are changing color in the local mountains, 1500 visitors have visited the site on several successive weekends. This caused traffic problems on the WT access road and local off-duty police were hired to control the traffic flow. Many foreign visitors from South America, Asia, and Europe as well as United States government and industry leaders have visited the site. In fact large numbers of foreign and domestic VIP groups occasionally have been disruptive to meeting Mod-1 Program Schedules. School classes, youth groups, professional organizations etc. are continually scheduling visits through the local Blue Ridge Electric Membership Corporation District Manager.

Assessment

The public reaction to the Mod-1 Wind Turbine Project has been demonstrated continually by the number of visitors to the site. The people have clearly expressed to Blue Ridge and site personnel their desire for pollution free electricity that is not dependent on foreign produced oil. The local people have expressed their desire to see the WT operating more of the time. The wind velocity is highest during the evening and early morning hours; therefore, they haven't observed it during much of the operating time. In addition configuring for testing causes periods of time when the WT can't be operated. In the opinion of the personnel involved with the WT from Blue Ridge, NASA and General Electric Company, the public, who have visited the site and the local Boone residents, are definitely in favor of producing electrical power via wind turbines generators.

6.0 CONTRIBUTIONS TO WT TECHNOLOGY

Introduction

Since the Mod-1 WT was the first modern megawatt class machine that had as its purpose research and development, a number of major contributions have been made to WT technology. These contributions resulted both from deliberate investigative efforts as well as from unexpected problems that occur during any "first of a kind" endeavor. The important WT technology developments that can be attributed to the Mod-1 program include innovative low cost WT design concepts and metal and composite blade fabrication/process techniques. The Mod-1 was the first remote unattended 2 megawatt WT to synchronize, generate power to a public utility system, and be controlled by a utility dispatcher. Computer codes were verified for dynamic and loads analysis, performance prediction and electrical stability analysis. These will be useful for future generation designs of megawatt class systems. Environmental impact issues, such as sound generation and TV interference, were experienced, evaluated, and solutions for wind turbines identified. And finally, a host of "lessons learned," including the importance of optimizing an installation site to WT characteristics, have been reported in the literature for the benefit of the WT industry.

Innovative Design Concepts

Just after the completion of the Mod-1 design, a Mod-1A configuration was designed and reported to the WT industry at a NASA workshop in March of 1979 that synthesized the innovative concepts that were a by-product of the Mod-1 design experience. These low cost concepts identified on the Mod-1A which were beyond the scope of the Mod-1 specification, have been incorporated in second and later generation WT's. These innovations are a soft tower, partial span control, a teetered hub and an upwind rotor. The utilization of these concepts with others, has resulted in cost effective WT's which are the keystone of the emerging commercial market.

Blade Manufacturing Technology

The manufacturing of the Mod-1 rotor blades, modern industry's initial attempt to construct a blade of 100 foot in length, established the fabrication technology for welding and stress relief of steel blades for the WT industry. The Mod-1 blades have performed successfully experiencing in excess of three quarters of a million cycles and "know how" from these blades has been incorporated in second generation steel welded blades. Also two composite fiberglass rotor blades designed specifically for Mod-1 have recently been manufactured, further establishing the Transverse Filament Tape (TFT) manufacturing process. One hundred foot blades once regarded as a challenge in the 1970's will be commonplace in the 1980's primarily as a result of the knowledge gained by the Mod-1 design and manufacturing experience.

Power Generation Feasibility

In the area of performance, the Mod-1 demonstrated that a multi-megawatt wind turbine could be successfully synchronized with a utility grid and generate stable electrical power meeting utility quality standards. Secondly, the Mod-1 demonstrated that an unattended WT could be operated remotely in conjunction with a utility system by a utility dispatcher in a fully automatic mode. Although power level varies significantly with wind speed and direction fluctuations, voltage flicker was well within utility standards. Transients associated with initial synchronization and WT shutdown exhibited a stable, acceptable behavior.

Environmental Impact

Perhaps the most significant contribution to WT technology resulted from the environmental impact of the Mod-1 in the Boone, North Carolina community. In the Fall of 1979, shortly after dedication, unanticipated complaints from local residents about objectionable sound and television interference caused by the WT were received by BREMC, the local utility. As a result, extensive efforts were conducted to characterize, establish standards, and solve sound and TV interference problems at Boone. The specific knowledge developed on the phenomenon was then incorporated into the second generation wind turbines.

In regard to sound, extensive measurements were made in the immediate vicinity of the WT and at remote residential locations, intermittently and continuously, and during daylight and evening hours at various weather conditions. These measurements were made at various WT rotational speeds, on line and off. The most important favorable impact of the Mod-1 experience at Boone resulted in an acute awareness throughout the WT industry of the WT noise generation problem. In addition to solving the Boone problem by reducing the rotor speed, this unexpected site specific environmental concern provided the impetus to characterize WT sound generation, develop predictive computer codes and establish WT sound standards. The body of knowledge that evolved from the Mod-1 experience is being incorporated in future generation designs and in utility site selection criteria.

A parallel story about TV interference unfolded in much the same manner to WT generated sound. Although not totally unexpected because of prior experience at Mod-0A sites, TV interference caused complaints within a 1-1/2 mile radius due to terrain which consequently restricted WT operation. An extensive measurement program was conducted that evaluated basic signal strength and interference characteristics. The results of the test program lead to the evaluation of three tentative solutions utilizing high gain residential antennas, cable TV and VHF to UHF rebroadcast translators. In the interim, however, the TV interference problem was eliminated by restricting the turbine operation to other than prime TV time. Thus far Mod-1 has contributed to the understanding and identification of solutions to this critical environmental problem that will affect future WT siting decisions.

7.0 CONCLUSIONS

Power Generation on Utility Grid

The WT has generated electrical energy within utility standards in a stable and well controlled manner. At 35 RPM transient wind conditions have had no adverse effect on the power generated or the machine. At 23 RPM the power generated was still within utility standards but the drive train was responding to its fundamental frequency.

Controls and Unattended Operation

The controls system initially presented a succession of minor problems and they were eventually solved. After the program acceptance tests, the control system performed flawlessly as designed. The WT was operated successfully in all modes including manual operation, automatic operation, unattended operation, and unattended remote control from the BREMC dispatchers office in Lenoir. In addition, the versatility of the control system allowed testing in various unconventional machine configurations during the Mod-1 Test Program.

TV Interference

Cable TV and rebroadcast via translators both provide excellent solutions to eliminate TV interference caused by wind turbines. Many areas of the country already have these systems installed. Because of the recent strong interest by the business community in providing these communication systems, cable TV and translator systems are being installed at a rapid rate throughout the country. This will be a definite advantage to the users of wind turbines.

WT Generated Sound

As a result of the sound test program conducted on the Mod-1, the sound emitted by WTs is now defined, understood and predictable. In addition, acceptable sound level standards for WTs are being established for WT manufacturers use. The meteorological effects on sound propagation and focusing of sound energy information will be an important criteria in WT site selections.

Drive Train Dynamics

When the WT was operated as originally designed at 35 RPM, the machine ran well, was compatible with the utility, and was dynamically very stable. When the WT was test configured to reduce the sound emitted at 23 RPM, the machine responded to its fundamental frequency in high turbulent winds, was compatible with the utility and was dynamically stable. A solution to the 23 RPM drive train fundamental frequency problem would be a more active blade pitch control system. This would increase the drive train damping which would permit the drive train to operate with less excitation of the first torsional mode in turbulent winds.

Public Reacton and Acceptance

The NASA, BREMC and GE personnel involved with the Mod-1 Program believe that the public who they have talked with at the site as well as the local residents around Boone have a very positive attitude toward using wind turbines to generate electrical energy. The large number of visitors and groups from foreign countries and the United States visiting the Mod-1 site in this remote mountain community attests to the popularity of this method of energy conversion.

Contributions to WT Technology

The Mod-1 Program has made substantial contributions to the development of WT technology. GE through the experience gained during the design phase of the program developed many low cost design concepts for the benefit of the wind turbine industry. Metal and composite blade manufacturing technology was also developed. The Mod-1 first demonstrated that a megawatt sized WT could be operated in an unattended fully automatic mode and generate utility quality power into a public utility system. Analytical computer codes for predicting wind turbine dynamic and loads analysis were verified from Mod-1 data. A significant contribution to the wind turbine industry was the discovery that the Mod-1 had an environmental impact on the community.

Project Objectives

The specific Mod-1 project orjectives, listed below, which were a part of the Federal Wind Energy Program, have all been achieved.

- Provided megawatt sized wind turbine operational and performance data.
- Demonstrated unattended, fail-safe operation.
- Involvement of utility as user and operator.
- Identification of maintenance requirements.
- Industry involvement in design, fabrication, and installation of the WT.
- Identify components/subsystems modifications to reduce cost, improve reliability and increase performance.

- Assess public reaction/acceptance of large wind turbines.
- Demonstrate compatibility with utility requirements.

8.0 ACKNOWLEDGMENTS

There have been many participants involved with the Mod-1 Program that have contributed to its success, and we thank you all for your excellent support which is appreciated. Particular thanks is extended to Mr. R. Puthoff, NASA-Lewis Research Center and Mr. R. Barchet of the General Electric Company for their outstanding contributions to the program. Successful completion of the program would not have been possible without the much needed project support from Messrs. G. Ayers, Jr., and R. Bumgarner of BREMC in North Carolina.

The following individuals, who are nationally recognized experts, and their organizations have made major contributions to portions of the program. We appreciate their excellent support and adjusting their busy schedules to be available when needed for conducting field tests, analyzing results, developing analytical prediction techniques, writing reports and attending meetings.

- Messrs. D. S. Sengupta, T. A. B. Senior, J. E. Ferris of the University of Michigan.
- Mr. J. F. X. Browne of John F. X. Browne Associates.
- Mr. R. J. Wells of GE Corporate Research and Development
- GE Corporate Research and Development Staff.
- Mr. N. Kelley of Solar Energy Research Institute.
- Messrs. G. C. Green, D. G. Stephens of NASA Langley Research Center.

We thank the two Mod-1 blade contractors and their project managers, Mr. J. Van Bronkhorst, Boeing Engineering and Construction, and Mr. W. Batesole, Kaman Aerospace Corporation, for their contribution to the program.

We also thank Messrs. J. Brown of GE and T. Miller of BREMC, who were at the site during the machine's assembly and continued during the operational period, for their outstanding support.

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2. Mod-1 Wind Turbine Generator Failure Modes and Effects Analysis, DOE/NASA/0058-79/1, NASA CR-159494, General Electric Company, Philadelphia, Pa., prepared for NASA under Contract NAS3-20058, Feb. 1979.

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4. Mod-1 Wind Turbine Generator Analysis and Design Report, DOE/NASA/0058-79/2-Vol. 1, NASA CR-159495, General Electric Company, Philadelphia, Pa., prepared for NASA under contract NAS3-20058, May 1979.

5. Batesole, W. R.: Fiberglass Composite Blades for the 2 MW Mod-1 Wind Turbine Generator, Kaman Aerospace Corporation, Bloomfield, Connecticut presented at DOE/NASA Workshop on Large Horizontal-Axis Wind Turbines, Cleveland, Ohio, July, 1981.

6. Sengupta, D.L., Senior, T. B. A. and Ferris, J. E.: "Measurements of Interference to Television Reception Caused by the Mod-1 WT at Boone, N.C. Technical Report on Contract No. DE-SERI-XH-0-9263-1, Solar Energy Research Institute, Golden, CO, 80401, January 1981.

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11. Thomson, D. W. and Roth, S. D.: Enchancement of Far Field Sound Levels by Refractive Focusing, The Pennsylvania State University, University Park, PA, 16802, presented at the second NASA Wind Turbine Dynamics Workshop, Clevelqand, Ohio, February 1981.

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13. Spera, D. A., Janetzke, D. C.: Performance and Load Data from the Mod-OA and Mod-1 Wind Turbine Generators, NASA, Lewis Research Center, Cleveland, Ohio presented at DOE/NASA Workshop on Large Horizontal-Axis Wind Turbines, Cleveland, Ohio, July, 1981.

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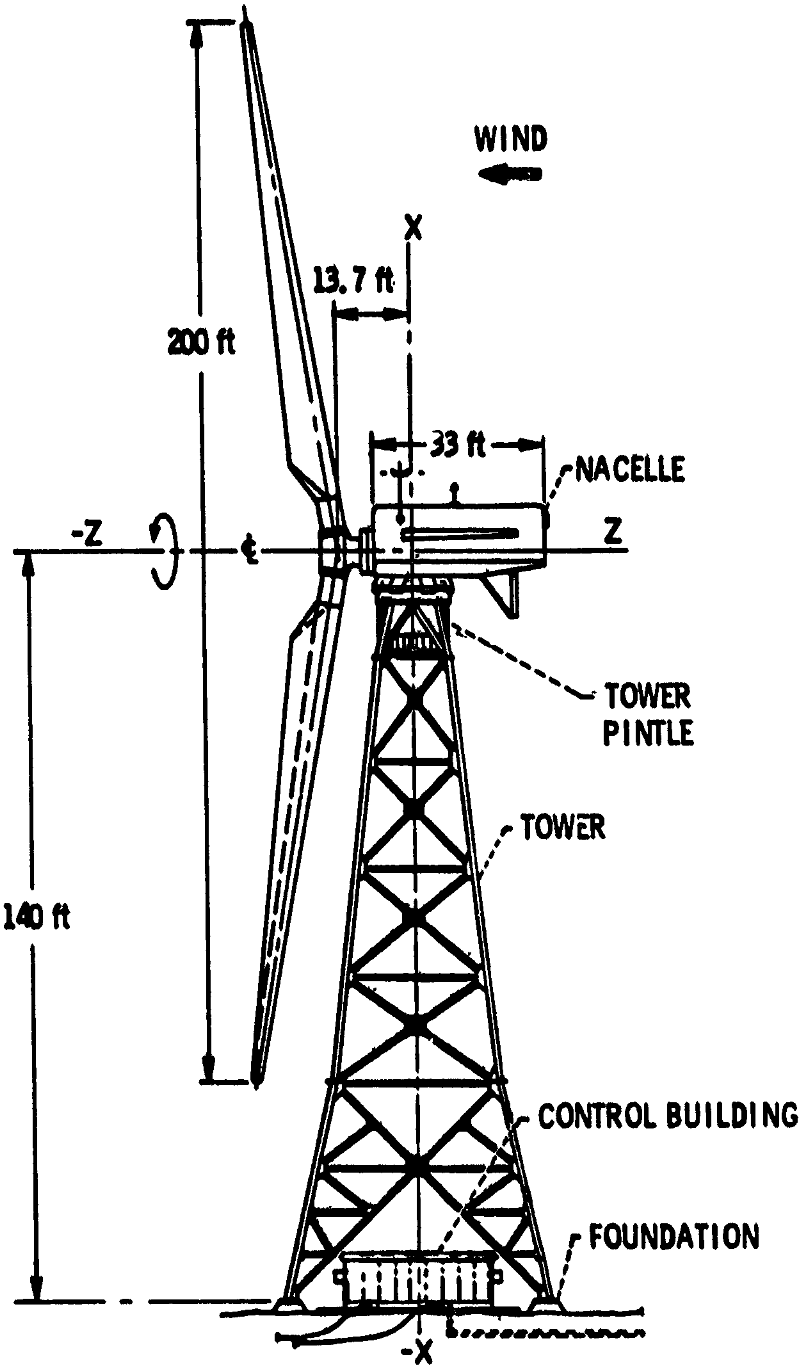

Figure 4.1-1. - Mod-1 2000-kilowatt wind turbine.

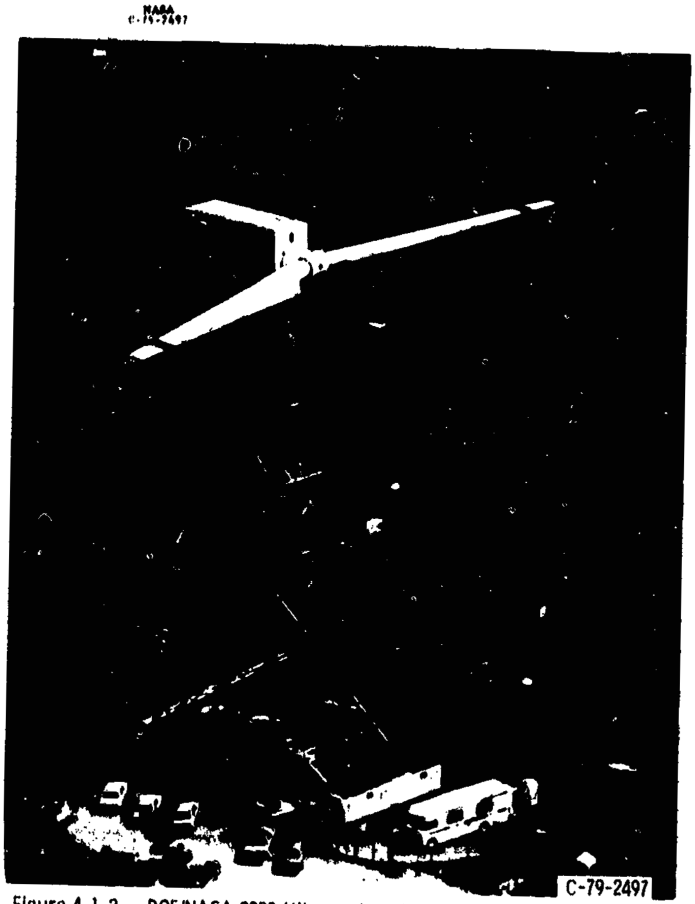

Figure 4.1-2. - DOE/NASA 2000-kW experimental wind turbine. Howard's Knob, Boone, North Carolina.

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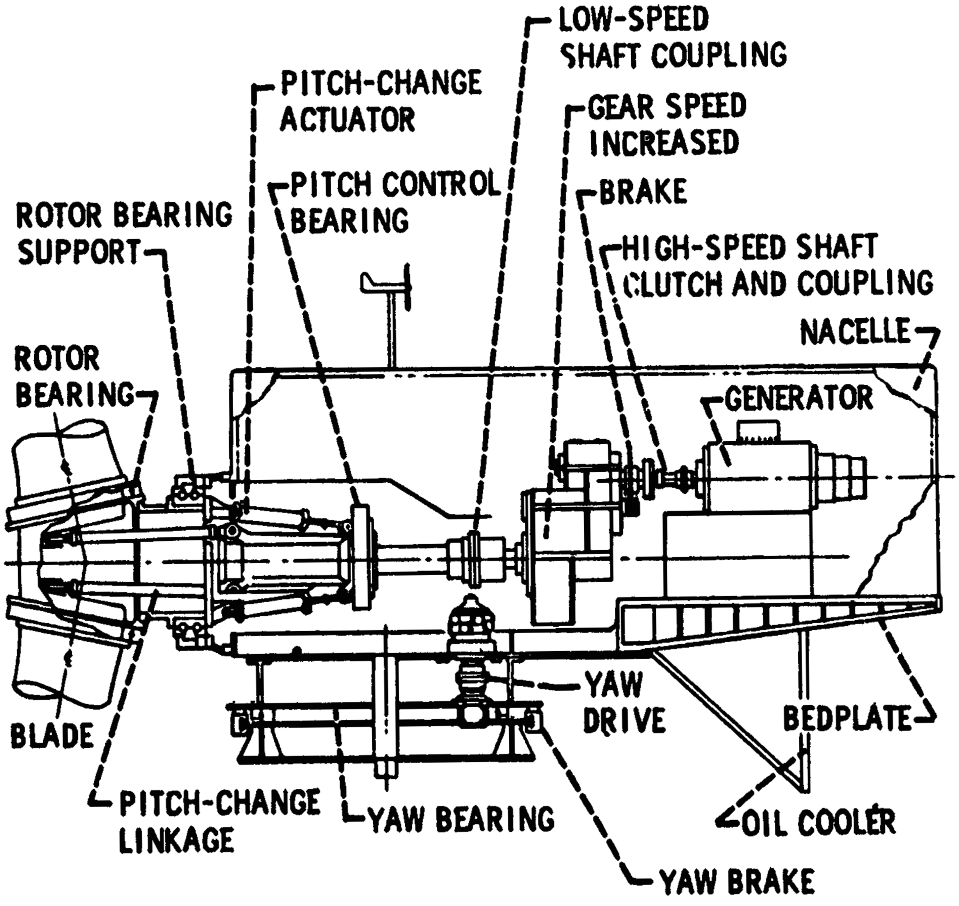
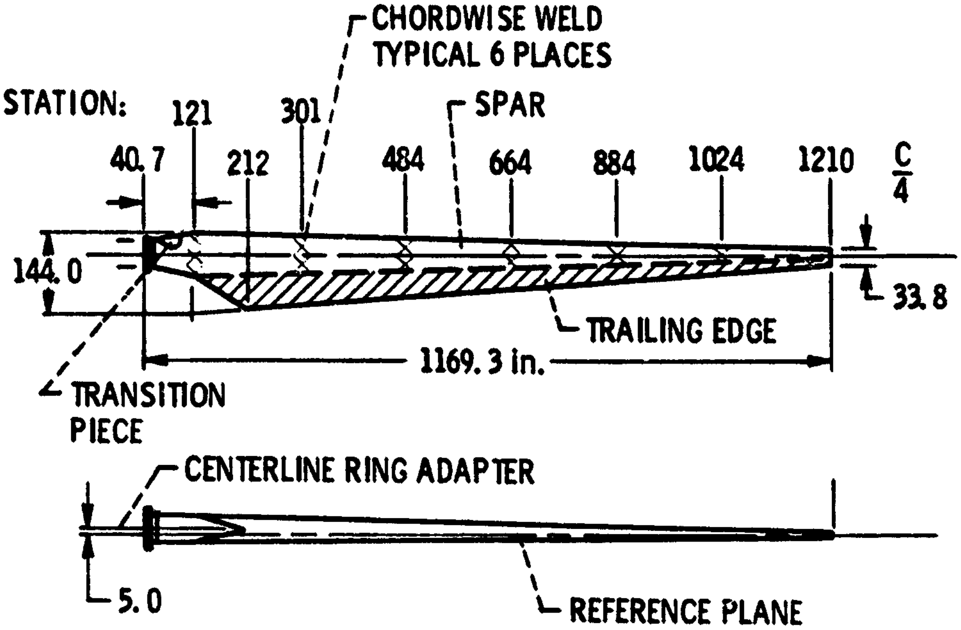
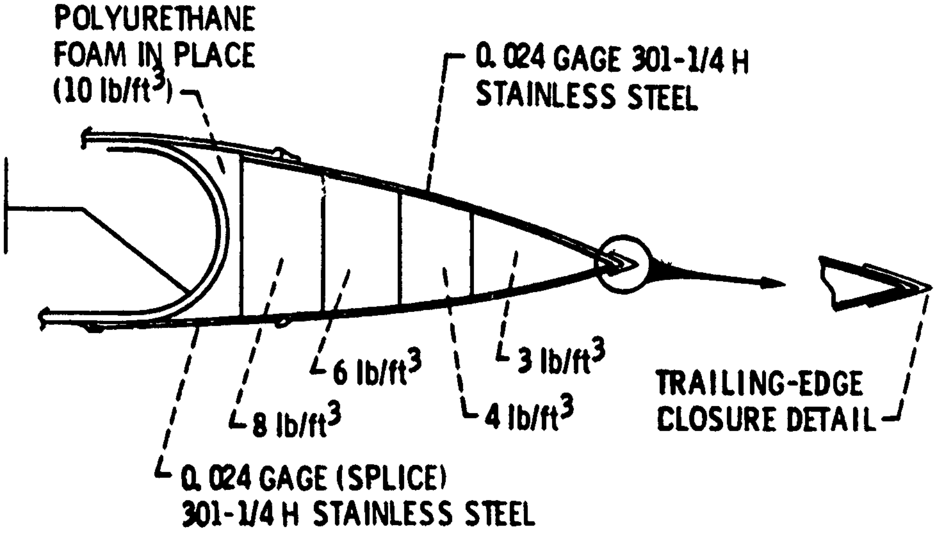


Figure 4.1-3. - Schematic diagram of the Mod-1 wind turbine assembly.



(a) BLADE GEOMETRY.



(b) TRAILING EDGE.

Figure 4.1-4. - Blade and trailing-edge geometry.

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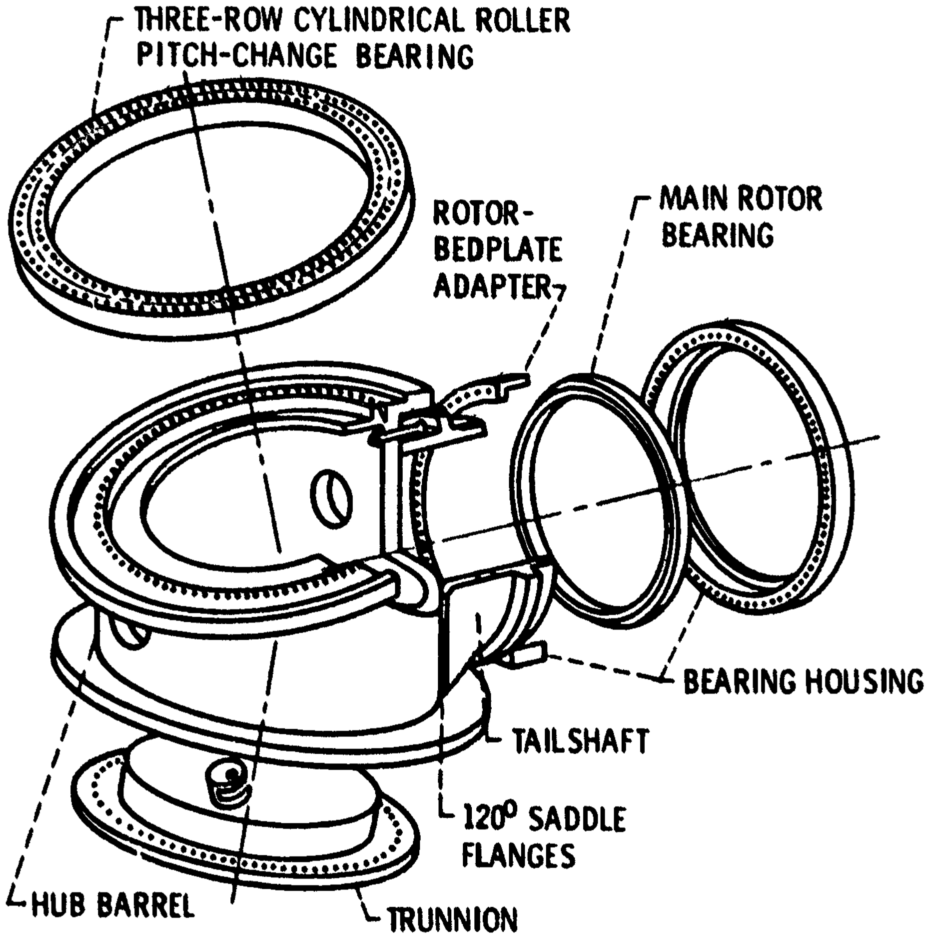

Figure 4.1-5. - Hub assembly.

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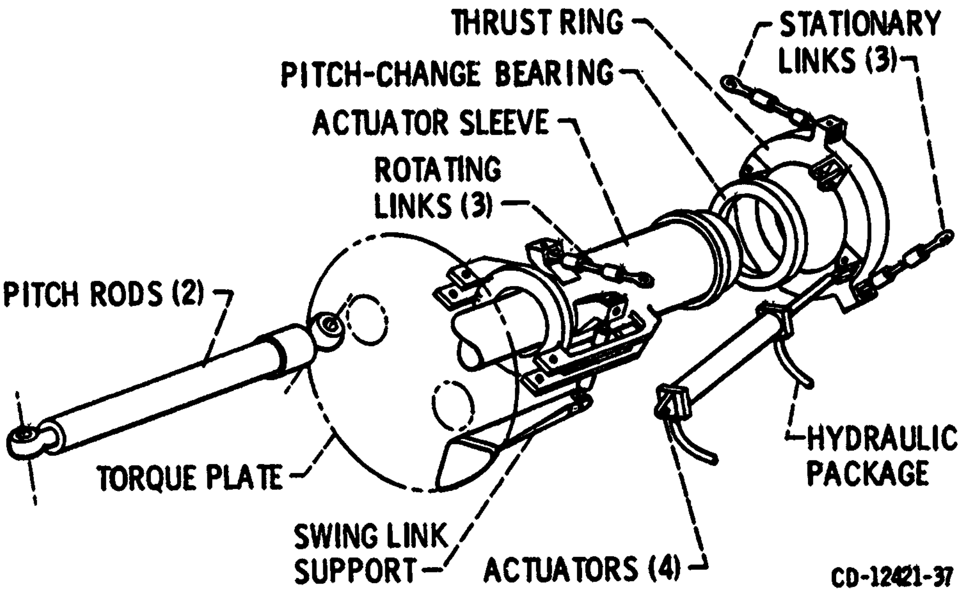

Figure 4.1-6. - Pitch-change mechanism.

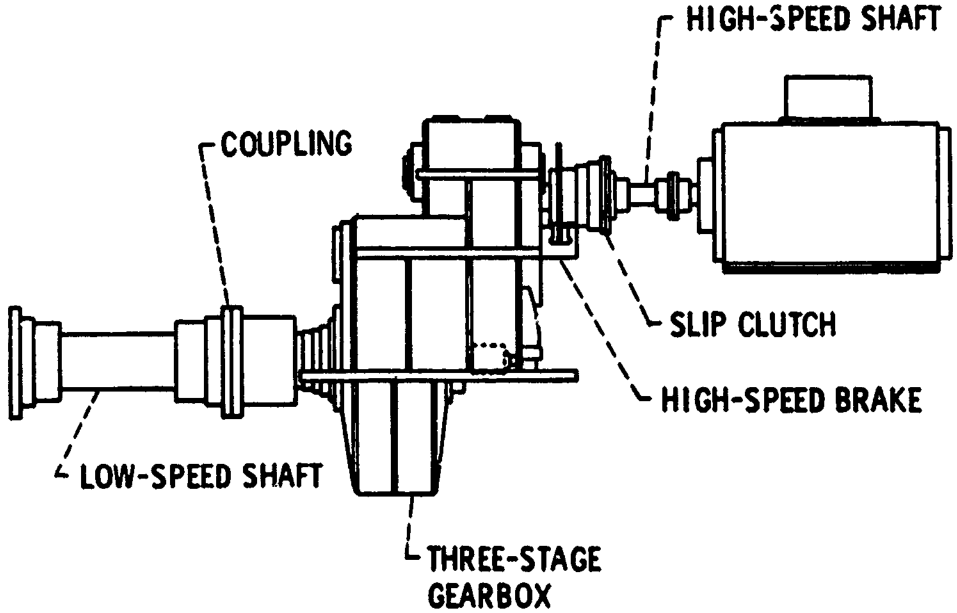

Figure 4.1-7. - Drive-train assembly.

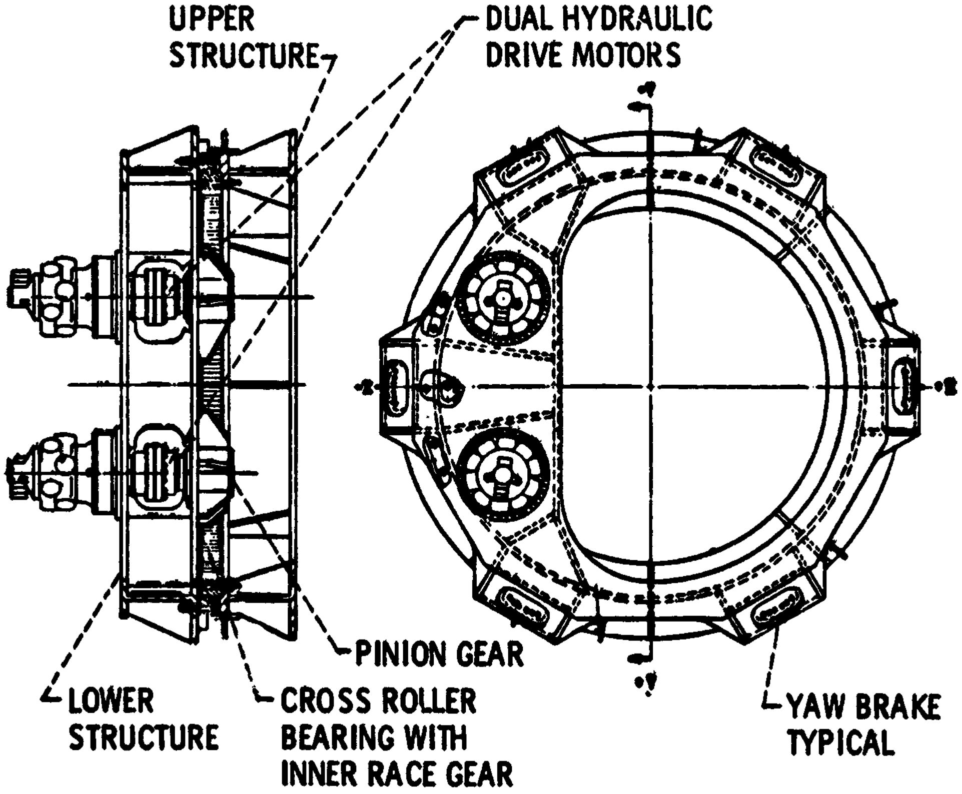

Figure 4.1-8. - Yaw drive assembly.

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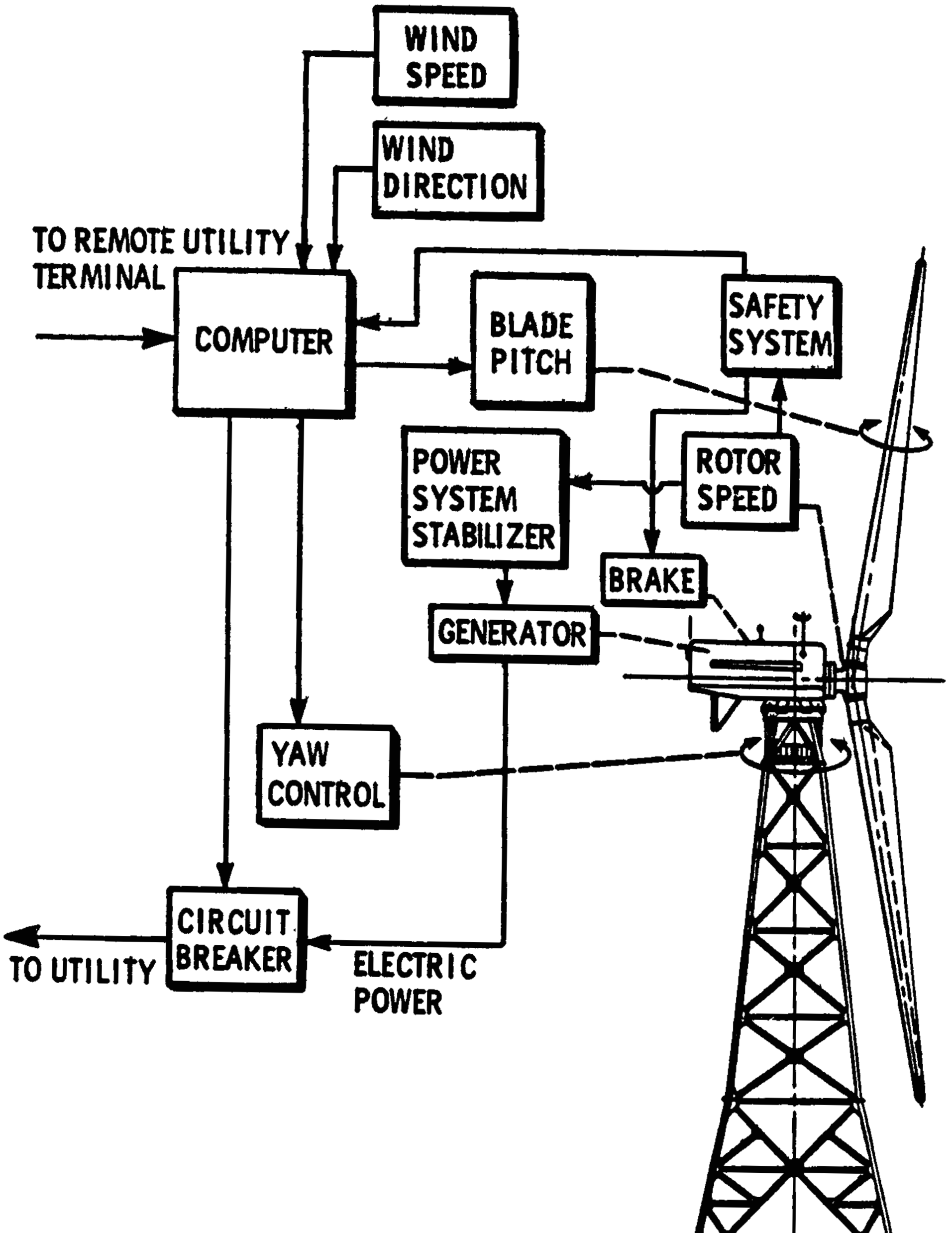
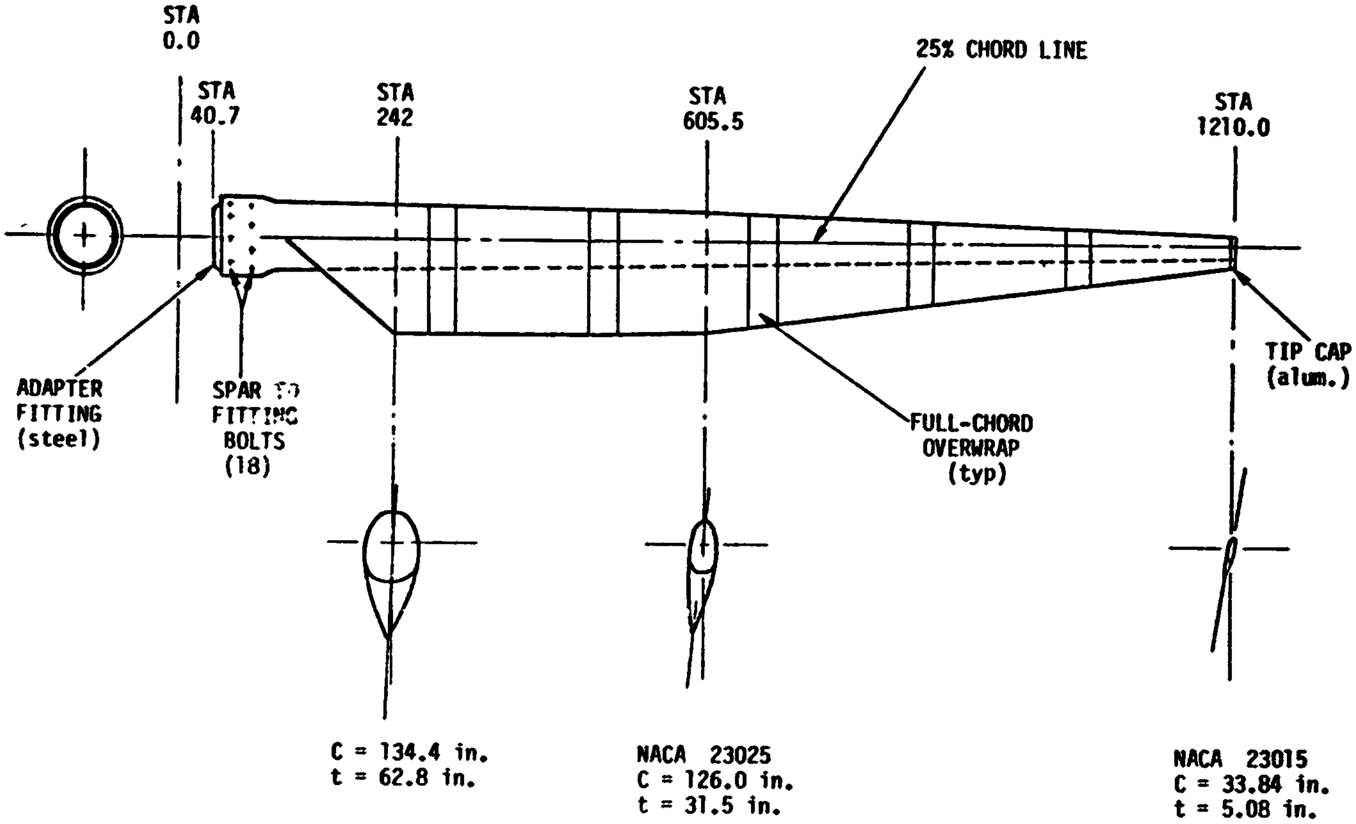


Figure 4.1-9. - Simplified Mod-1 control schematic.



MOD-1 COMPOSITE BLADE

FIGURE 4.2-1

11° LINEAR TWIST, ROOT TO TIP
23000 SERIES AIRFOIL
WEIGHT WITH ADAPTER: 26,846 lb.

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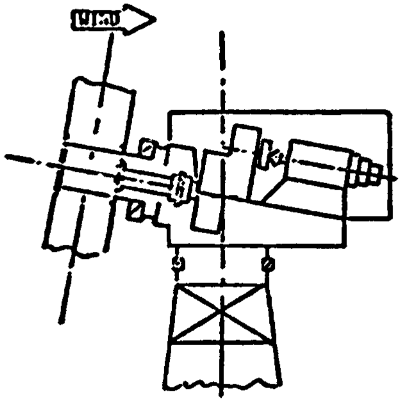
	MOD-1	MOD-1A
WIND REGIME	18 MPH	18 MPH
RATED POWER	2000 kW	2000 kW
LIFE	30 YEARS	30 YEARS
WEIGHT	655,000 LBS	400,000 LBS
2ND UNIT COST ($/kW)*	2,900	1,000
COST OF ENERGY (¢/kW-HR)*	18	5

*1978 $

MOD-1A OBJECTIVES

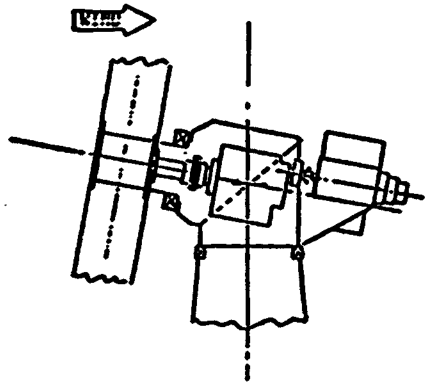
Figure 4.3-1



DESIGN CONCEPT #1
(REDUCED MOD - 1)

- FIXED HUB
- 2 BLADES
- UPWIND ROTOR
- PARTIAL SPAN CONTROL
- MOD-1 GEARBOX
- MOD-1 ELEC. GEN.
- TRUSS TOWER (SOFT)

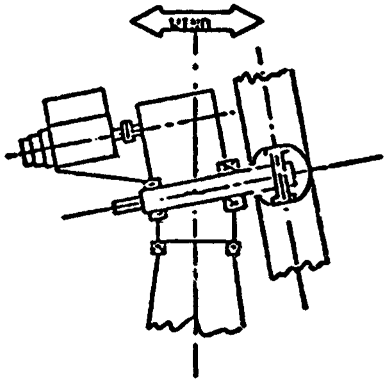
TOTAL WEIGHT
340,000 LBS



DESIGN CONCEPT #2
(EPICYCLIC GEAR)

- FIXED HUB
- 3 BLADES
- UPWIND ROTOR
- PARTIAL SPAN CONTROL
- EPICYCLIC GEARBOX
- MOD-1 ELEC. GEN.
- SHELL TOWER (SOFT)

TOTAL WEIGHT
355,000 LBS



DESIGN CONCEPT #3
(INTEGRAL GEARBOX)

- TEETERED HUB
- 2 BLADES
- DOWNWIND OR UPWIND
- PARTIAL SPAN CONTROL
- MOD-1 GEAR DRIVE
- MOD-1 ELEC. GEN.
- SHELL TOWER (SOFT)

TOTAL WEIGHT
320,000 LBS

FAVORABLE RESULTS COMPARED

TO MOD-1 WEIGHT OF 655,000

MOD-1 TRADE-OFF STUDY
CANDIDATES

Figure 4.3-2

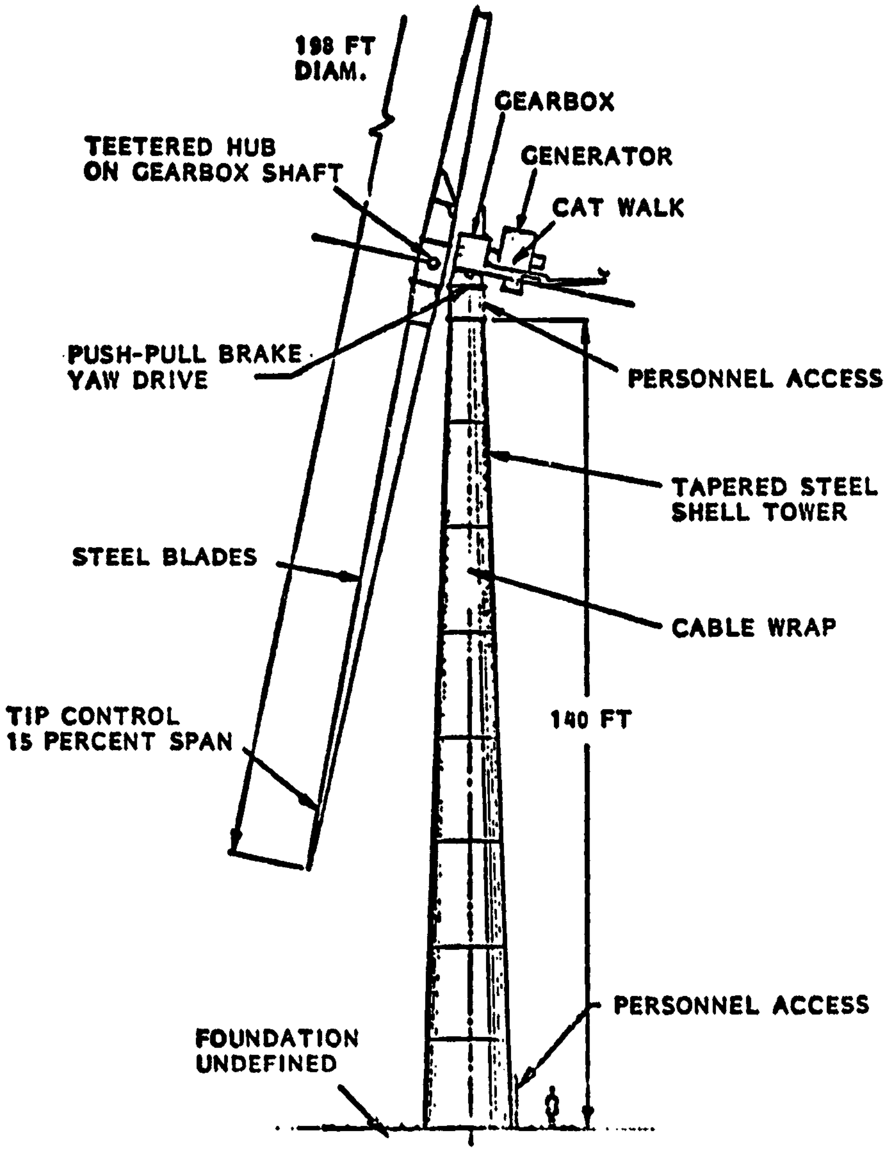


FIGURE 4.3-3 MOD-1A OUTLINE

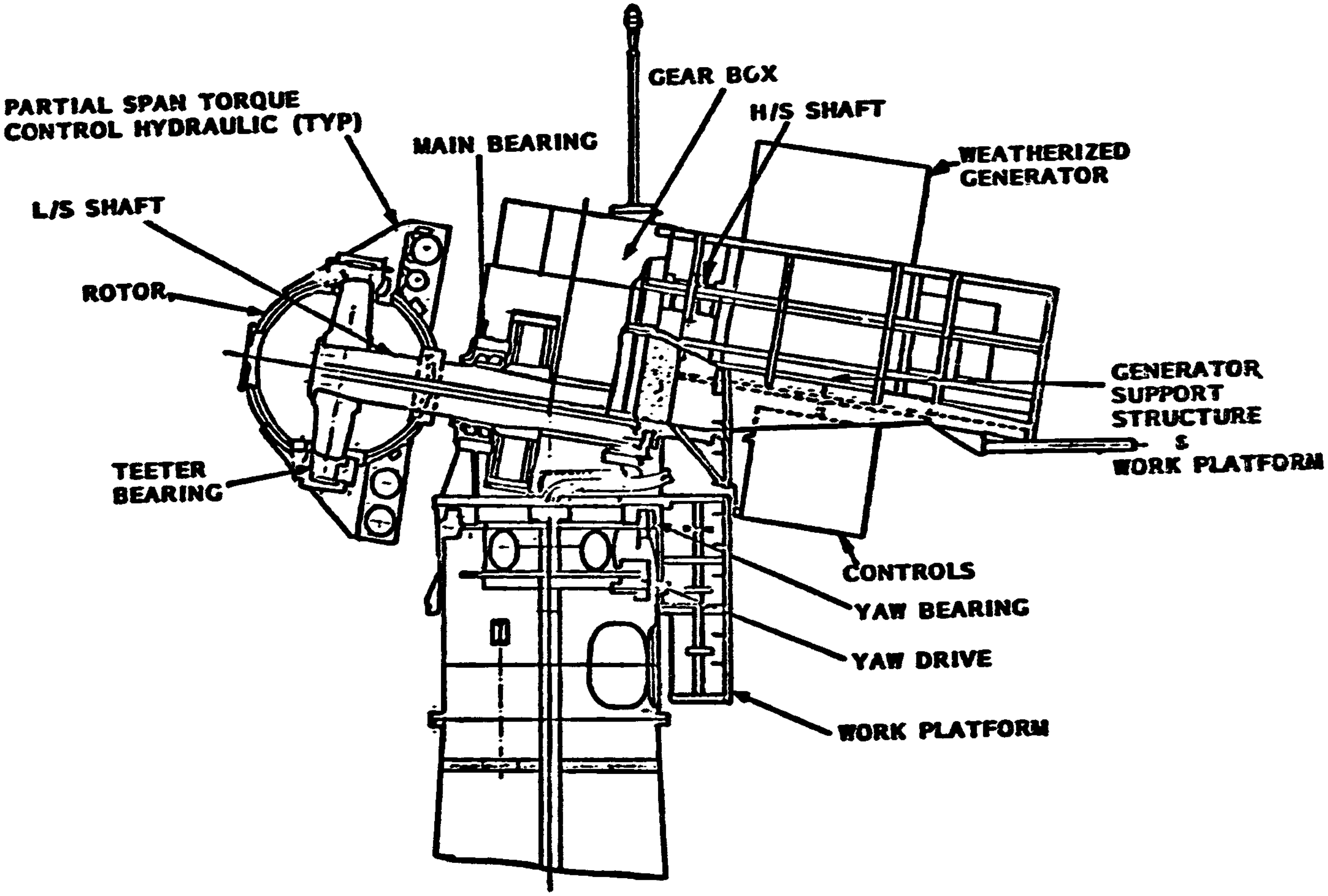
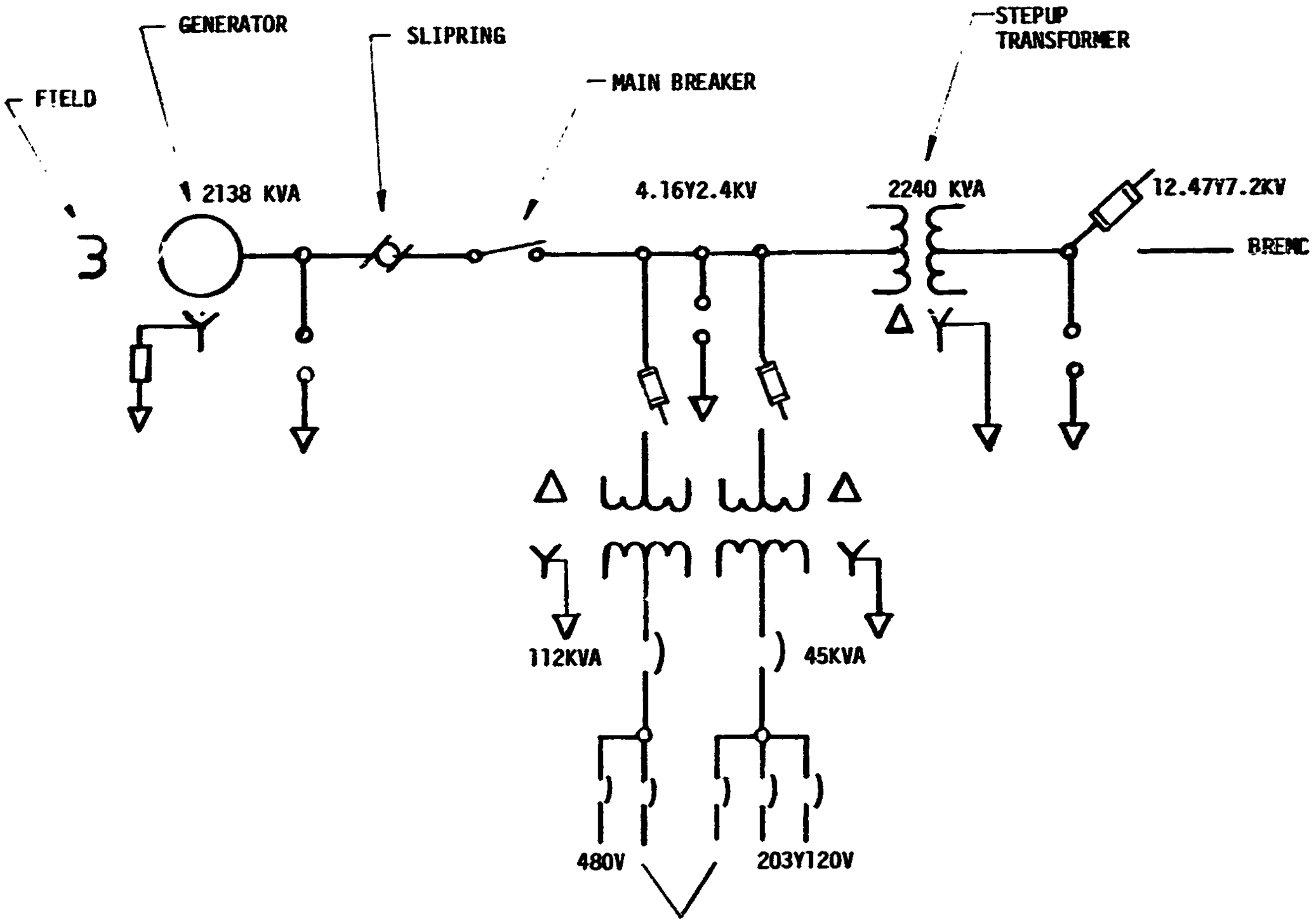


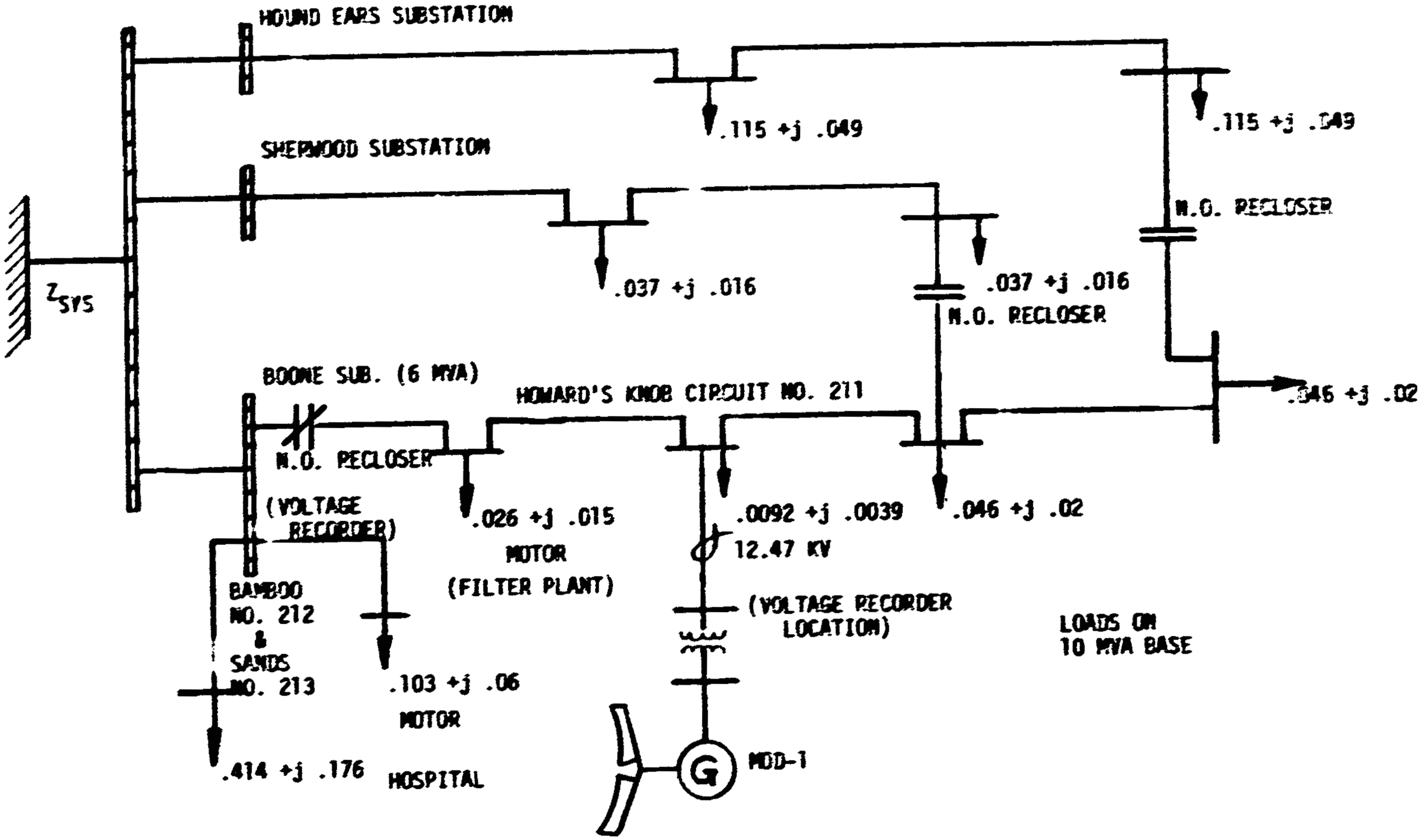
FIGURE 4.3-4 MOD-1A NACELLE



AUXILIARY CIRCUITS

POWER SYSTEM

SIMPLIFIED ONE-LINE DIAGRAM
Figure 5.1-1



ONE LINE DIAGRAM OF BREMC DISTRIBUTION SYSTEM

Figure 5.1-2

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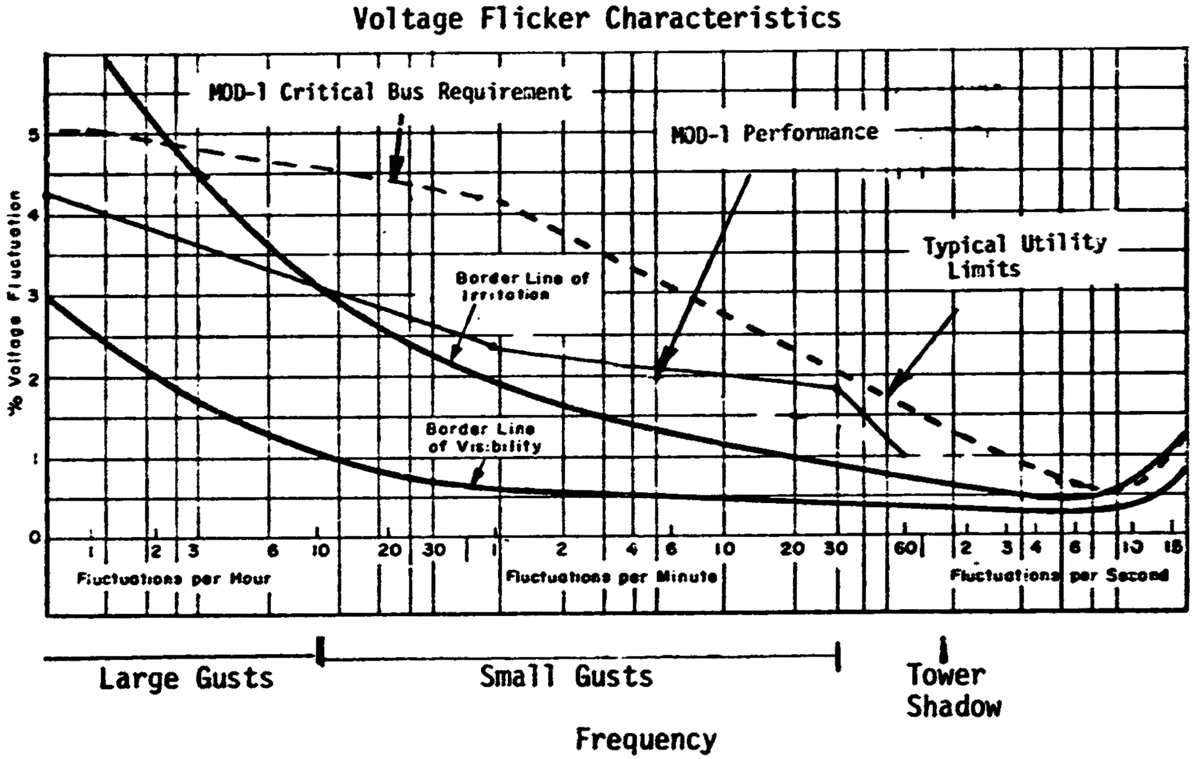
Voltage Flicker Characteristics
MOD-1 Critical Bus Requirement
MOD-1 Performance
Typical Utility Limits
Border Line of Irritation
Border Line of Visibility
% Voltage Fluctuation
0
1
2
3
4
5
1
2
3
6
10
20
30
1
2
4
6
10
20
30
60
2
3
4
6
10
18
Fluctuations per Hour
Fluctuations per Minute
Fluctuations per Second
Large Gusts
Small Gusts
Tower Shadow
Frequency

Figure 5.1-3

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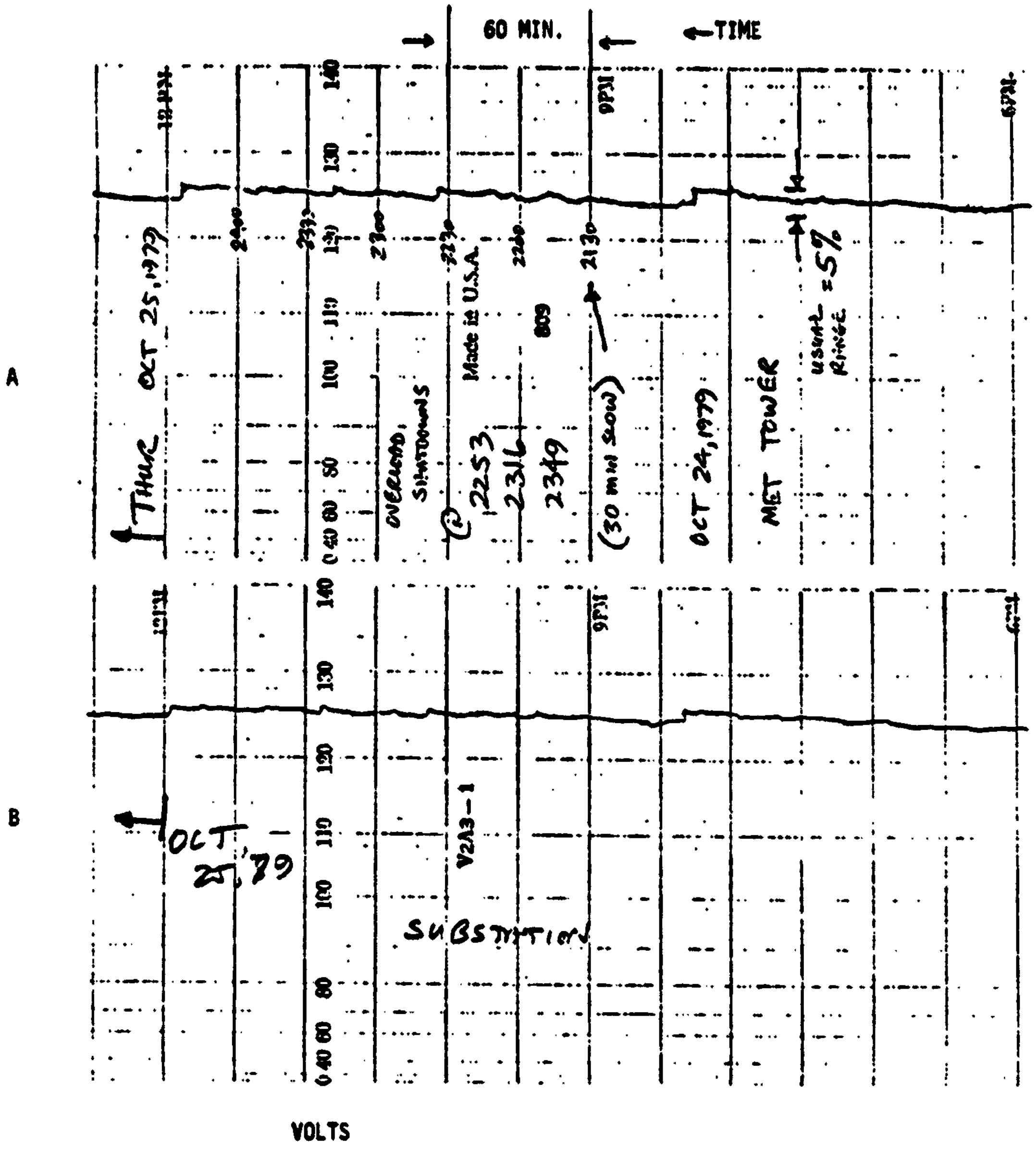
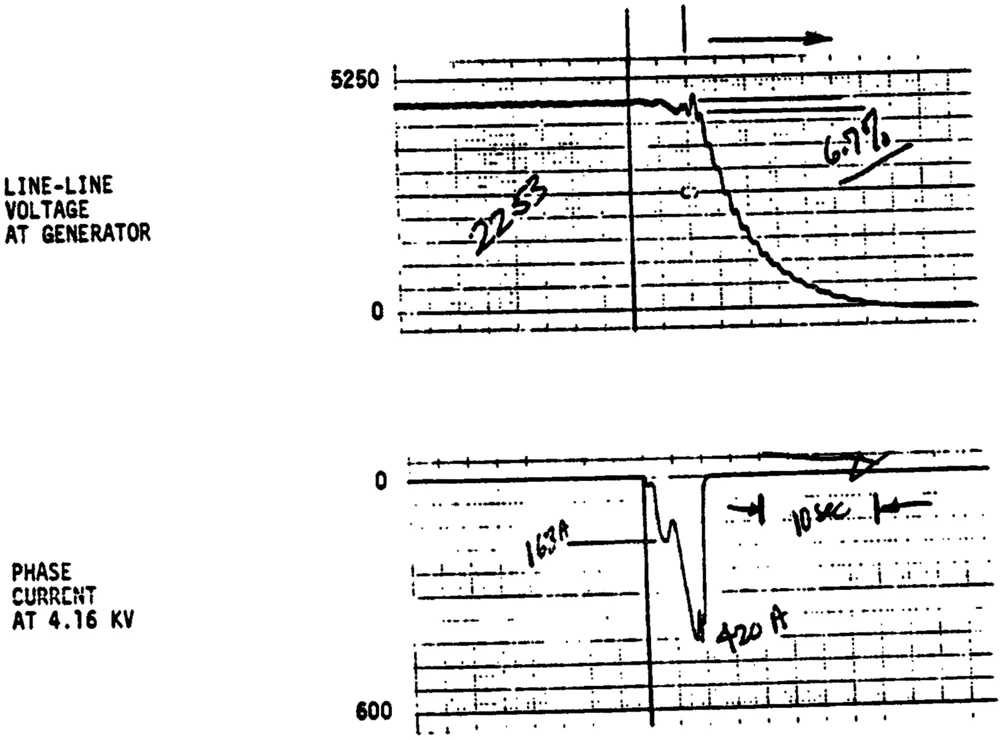


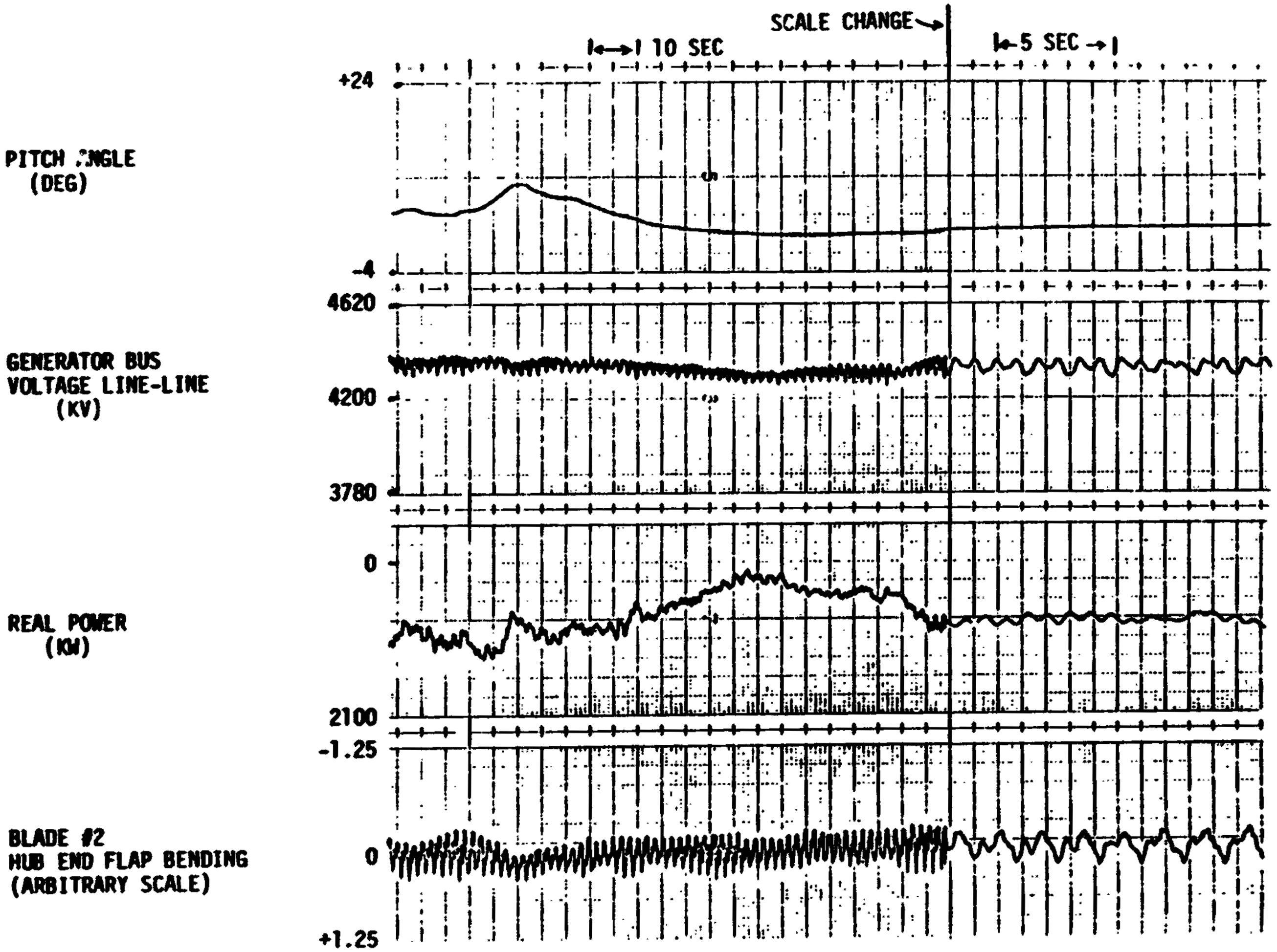
UTILITY VOLTAGE RECORDER TRACES
OCTOBER 24, 1979

Figures 5.1-4a and 5.1-4b



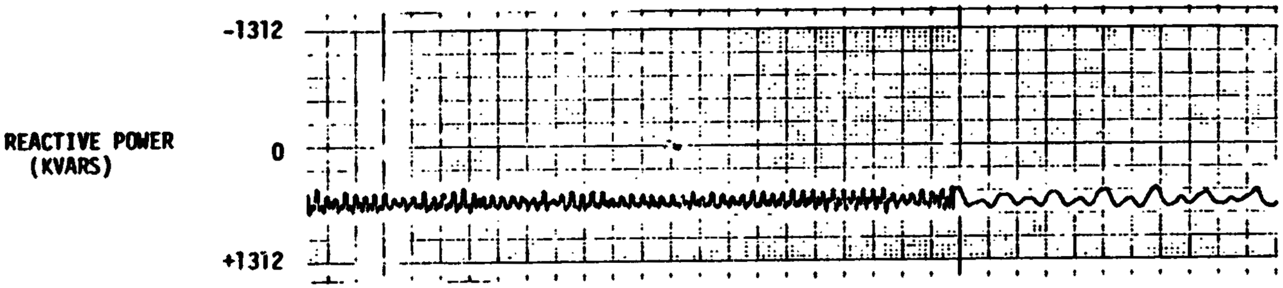
TRANSIENT ON OCTOBER 24, 1979

Figure 5.1-4c



MOD-1 OPERATION AT 34.7 RPM
JANUARY 31, 1980

Figure 5.1-5a



MOD-1 OPERATION AT 34.7 RPM
JANUARY 31, 1980

Figure 5.1-5b

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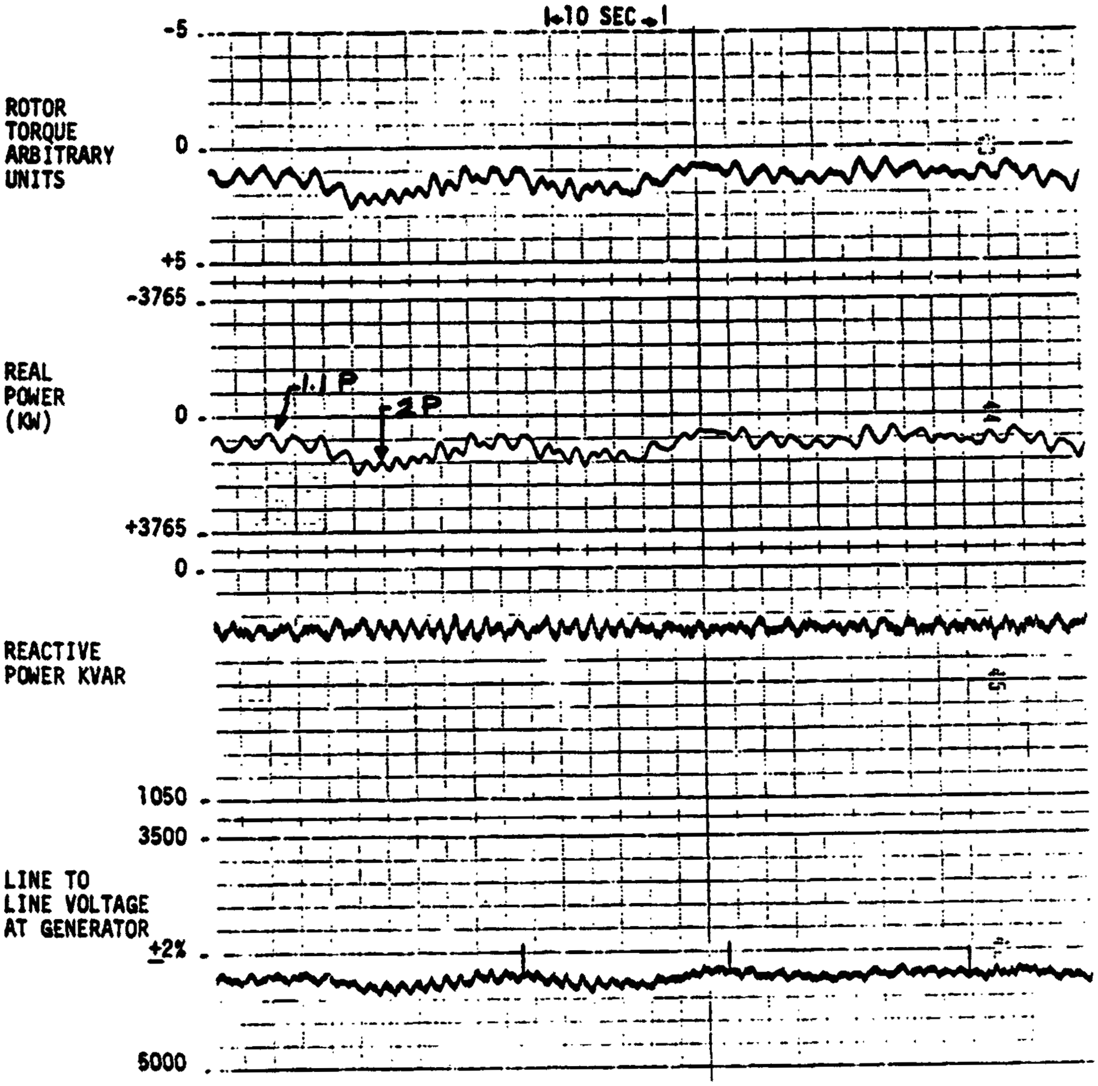

TYPICAL 23 RPM OPERATION
JANUARY 19, 1981, 0816 HRS

Figure 5.1-6

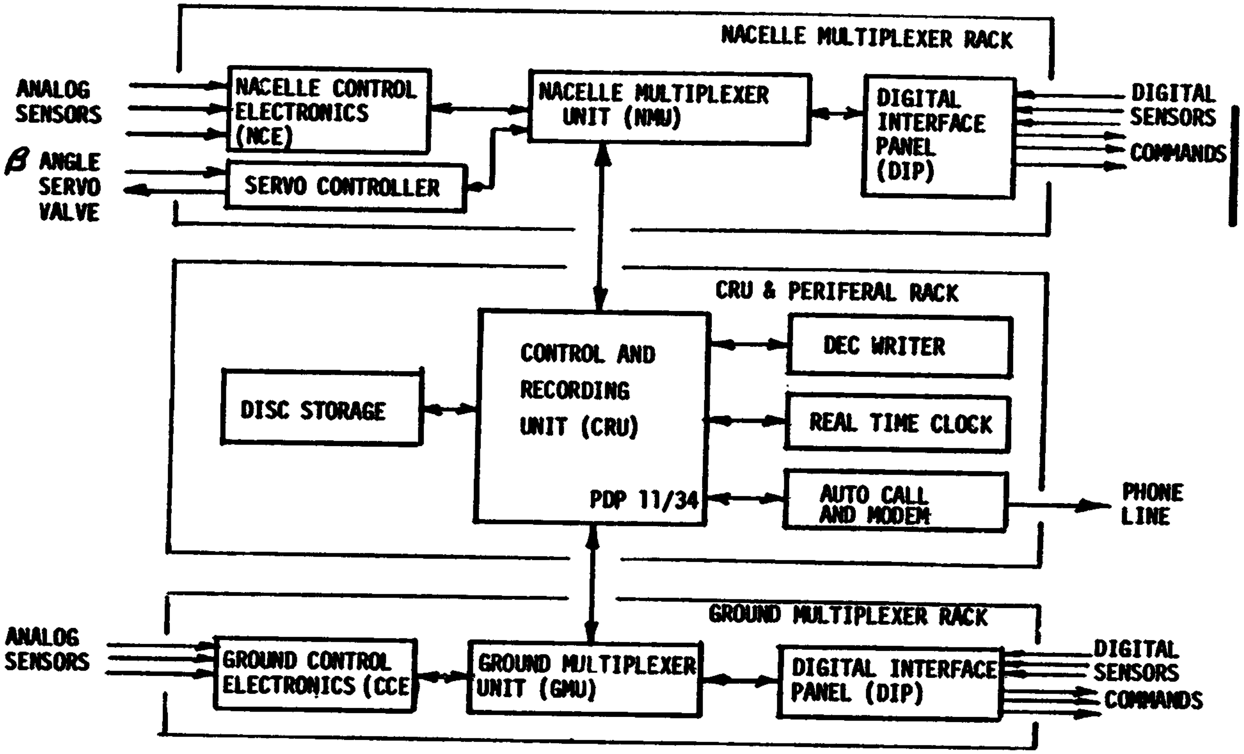

Figure 5.2-1. Control Subsystems Block Diagram

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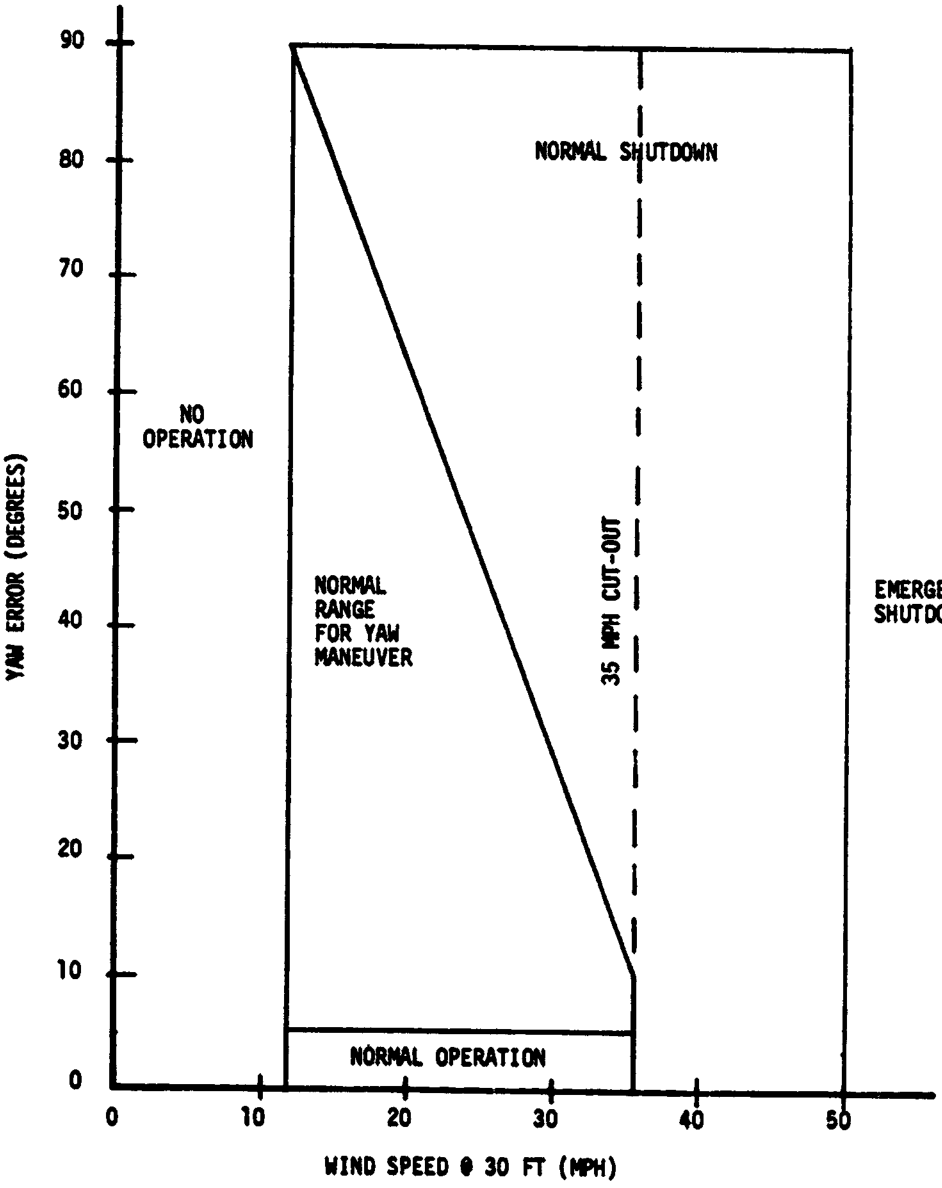

Figure 5.2-2. MOD-1 Operational Envelope

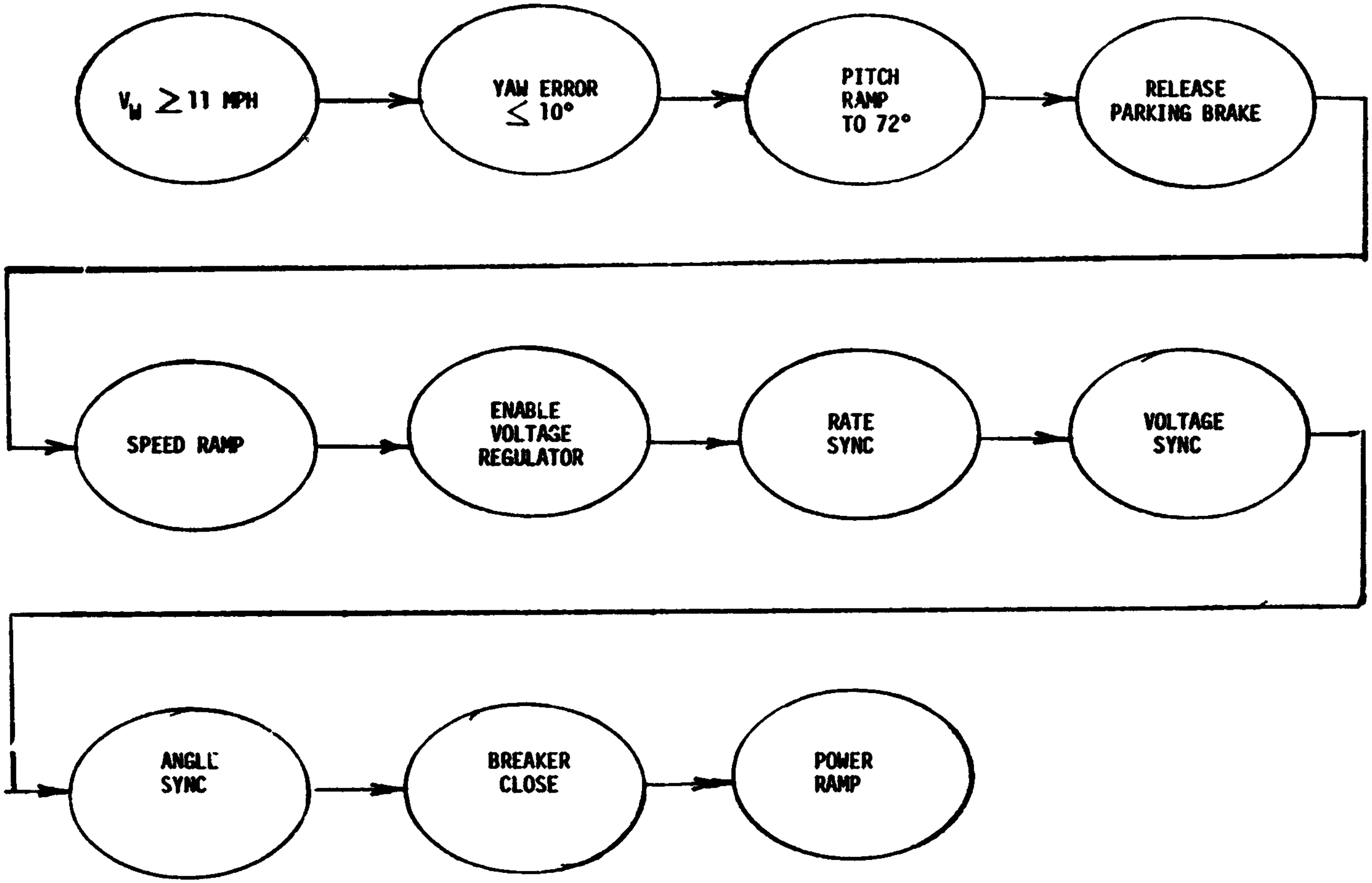

Figure 5.2-3. Startup Control Functions

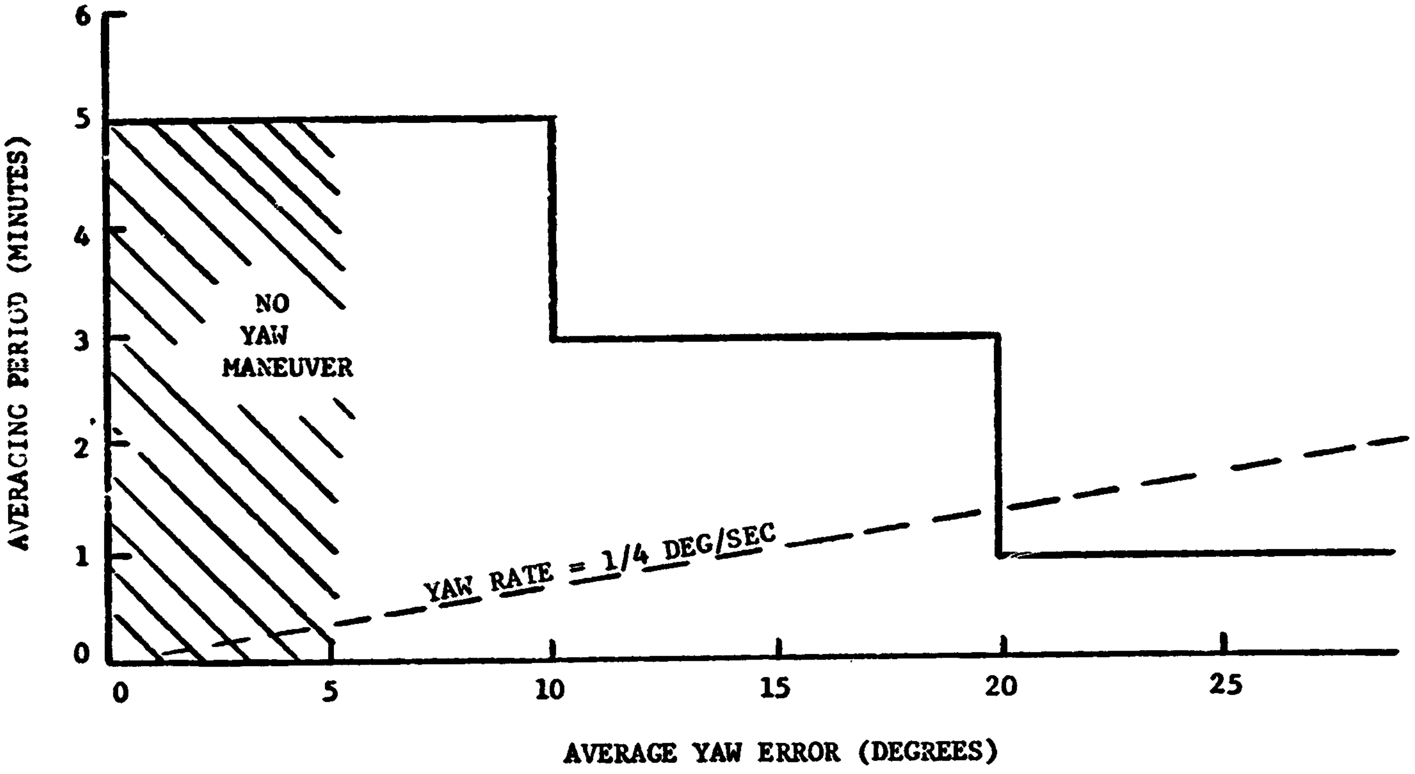

Figure 5.2-4. Yaw Correction Averaging Logic

FIGURE 5.3-1: Topographical map of the Boone area

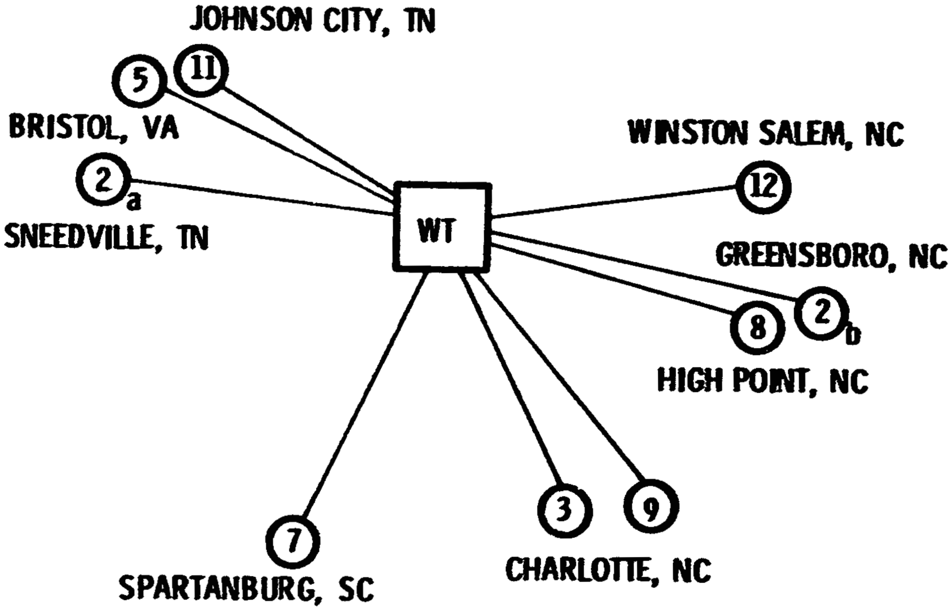

Figure 5.3.1-1. - TV stations received in Boone.

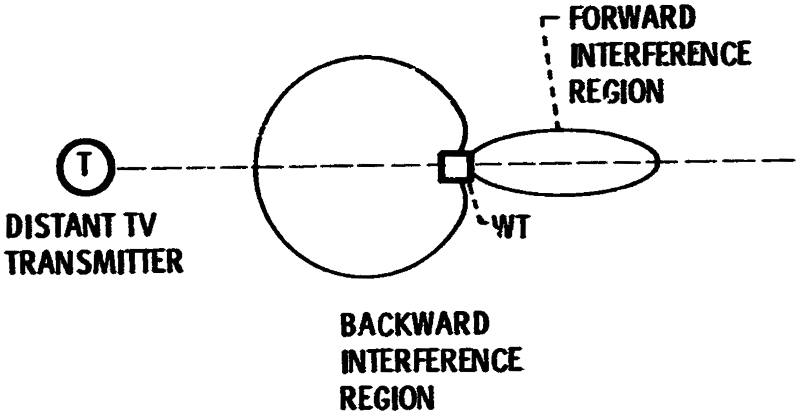

Figure 5.3.1-2. - Television forward and backward interference regions for a wind turbine.

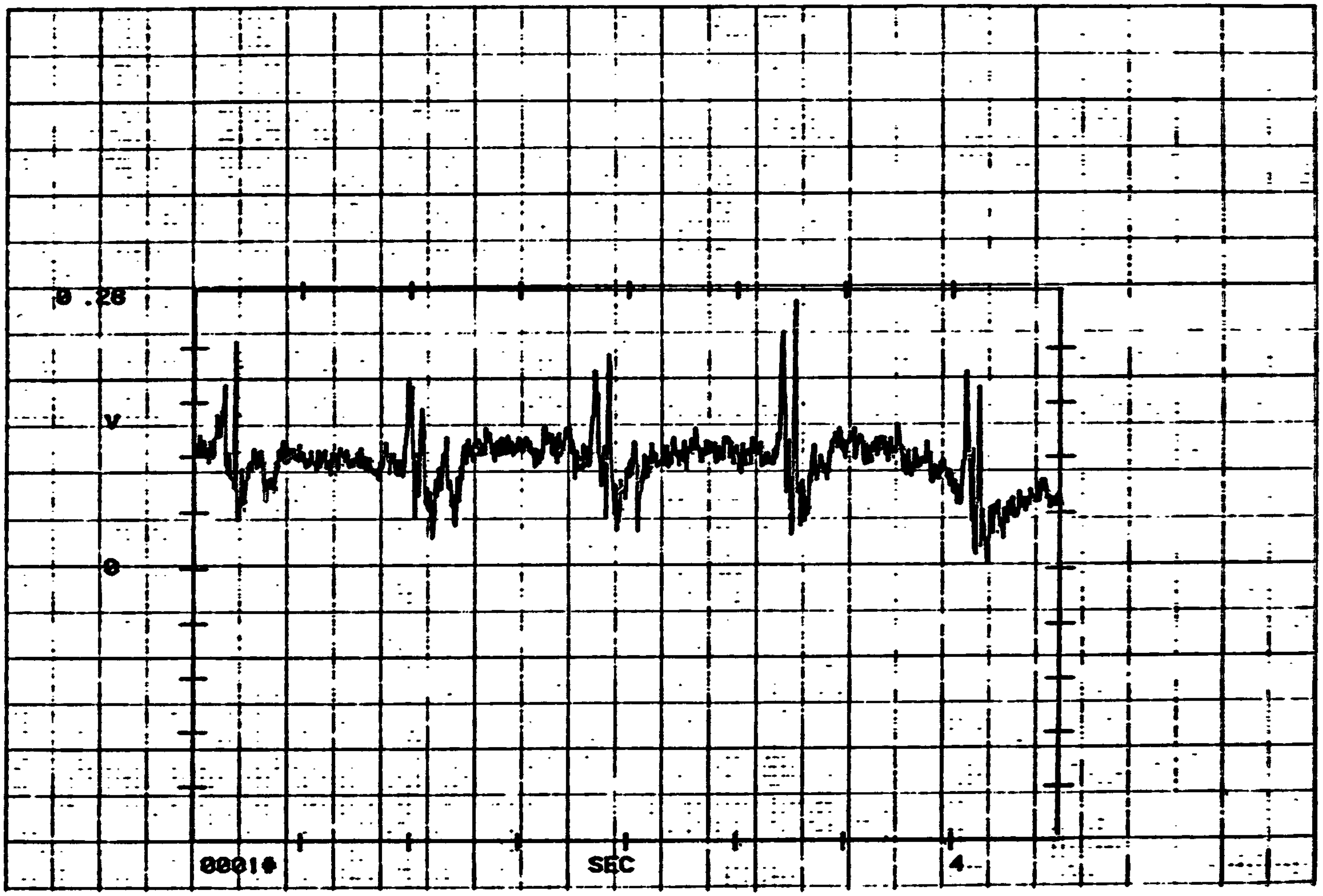

FIGURE 5.3.2-1 Impulse Sequence Near Machine, 35 rpm, 500 KW, April 1, 1980

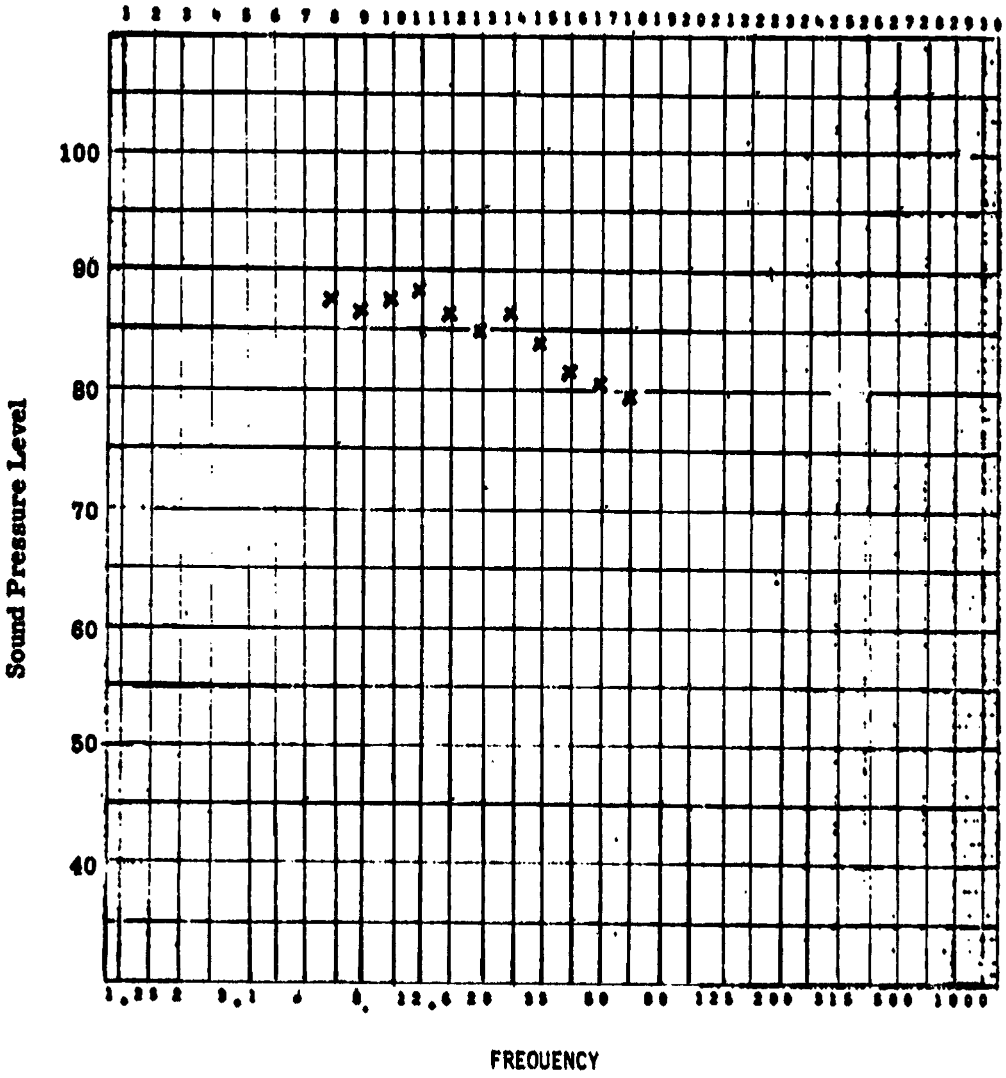

Figure 5.3.2-2. Sound Pressure Levels
1000 KW 50' From WT
February 12, 1980

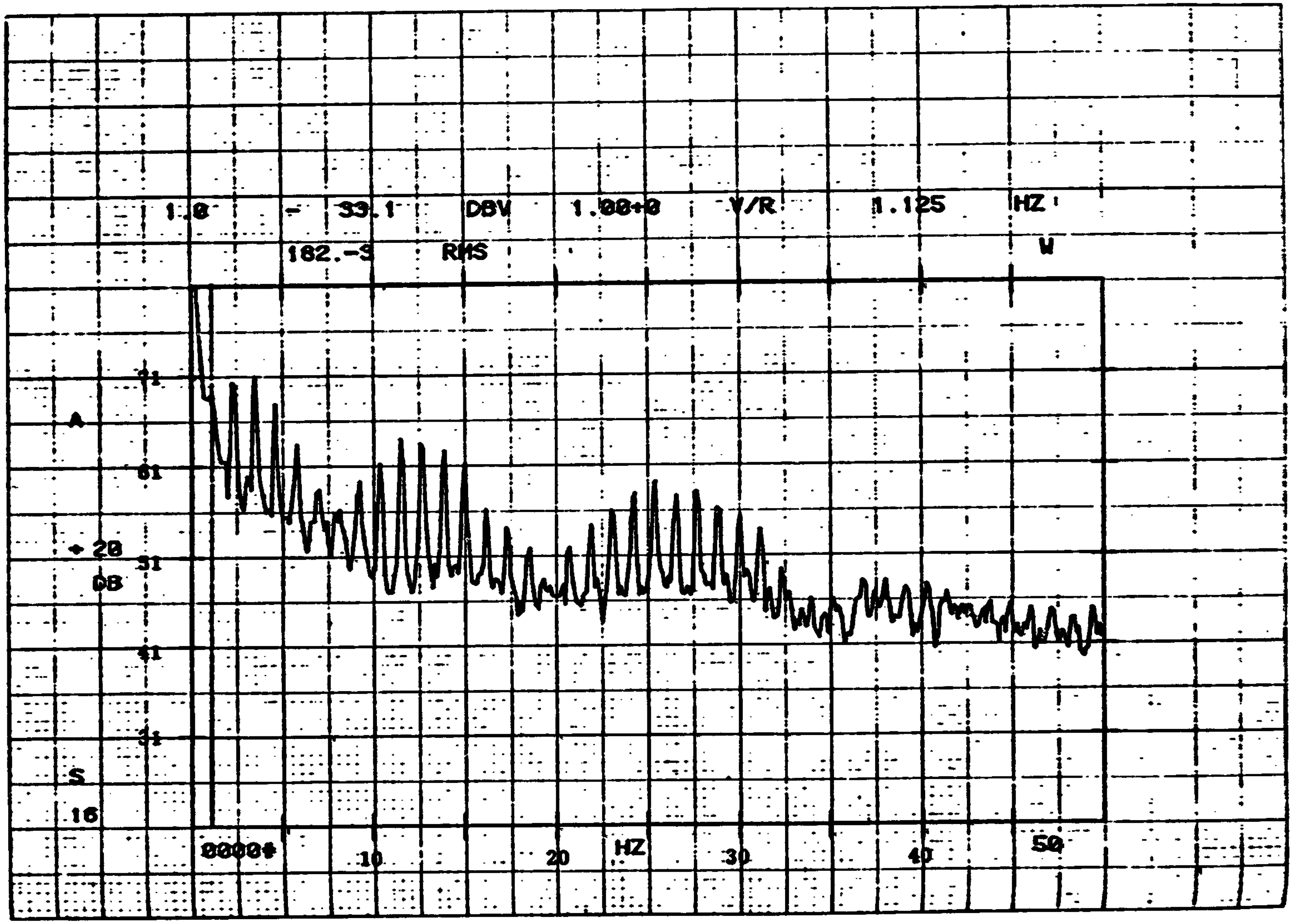

Figure 5.3.2-3. Sound Pressure Levels Versus Frequency Outside Residence 12:07 P.M., March 31, 1980

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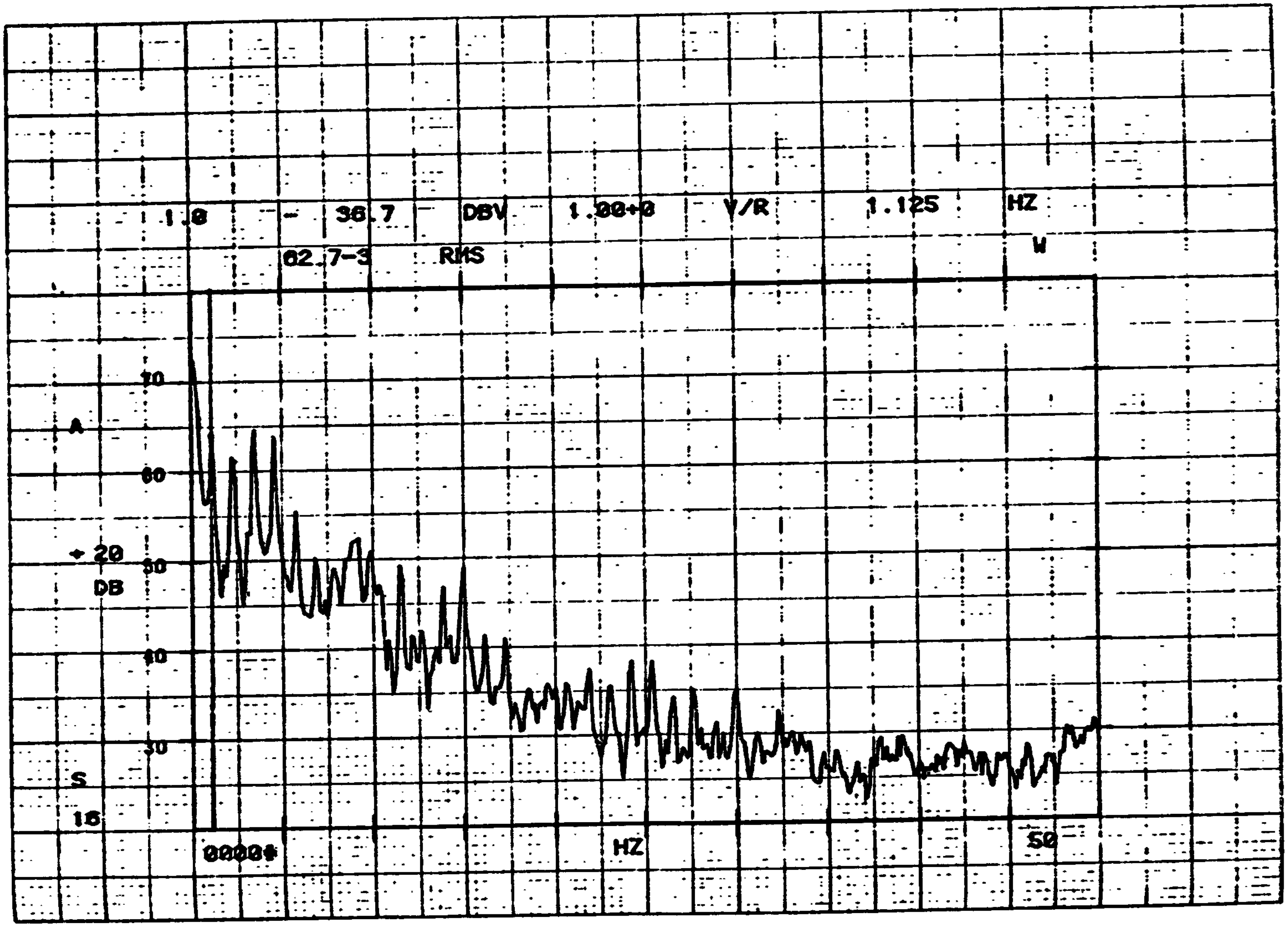

Figure 5.3.2-4. Sound Pressure Level Versus Frequency Inside Residence
12:07 A.M., March 31, 1980

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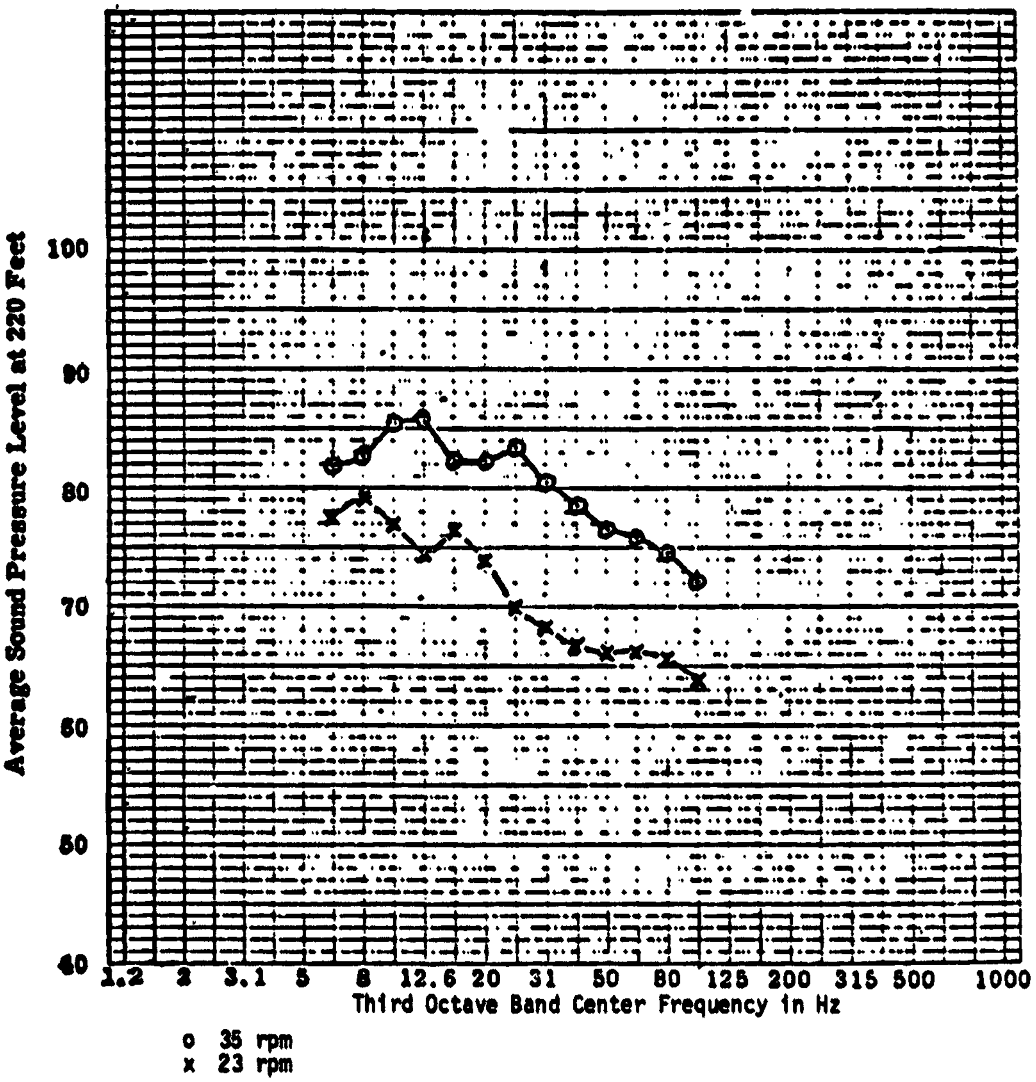


Each curve represents average sound pressure levels for seven sets of data -- with different but comparable wind conditions and load.

Figure 5.2.2-5. Average Sound Pressure at 35 and 23 RPM

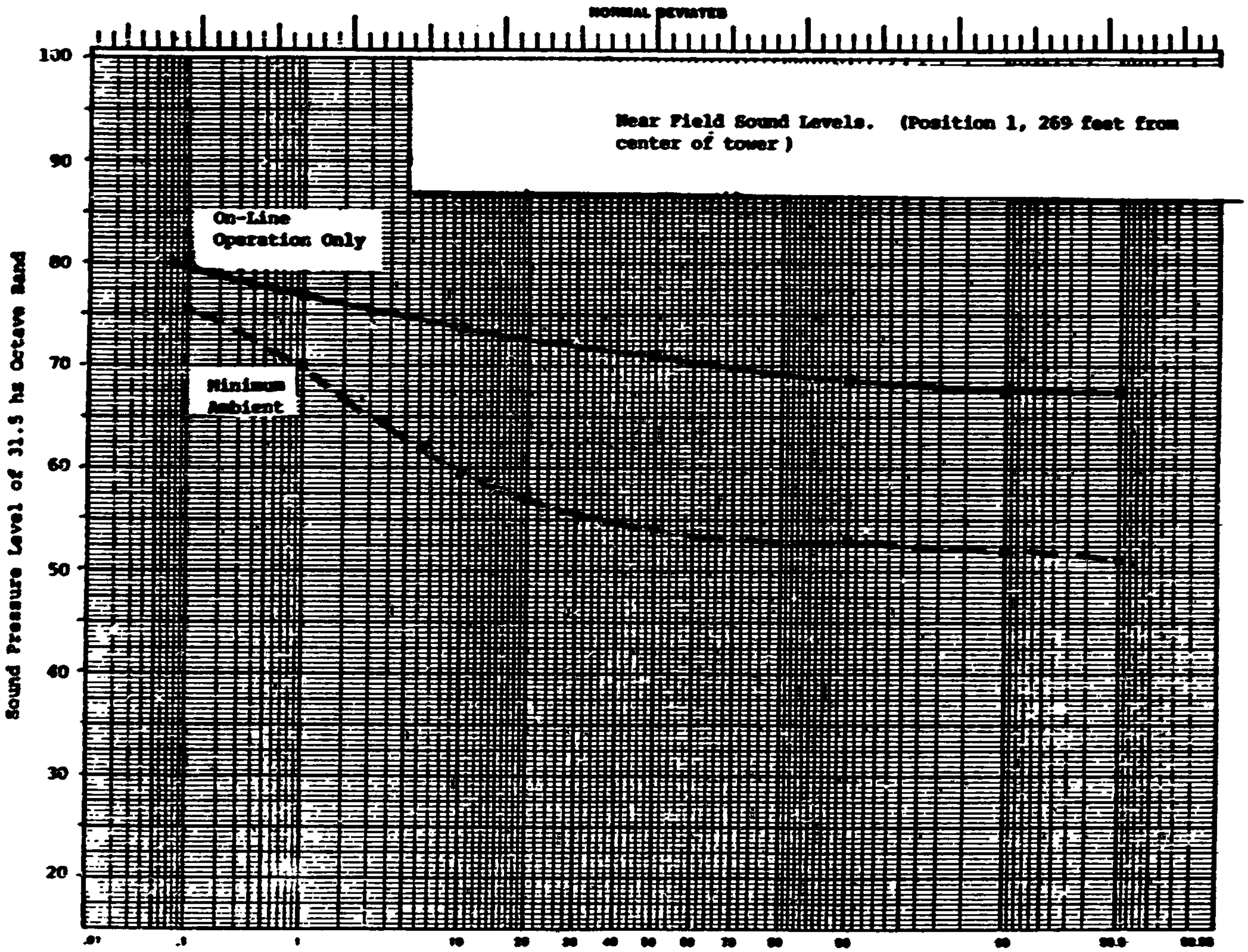
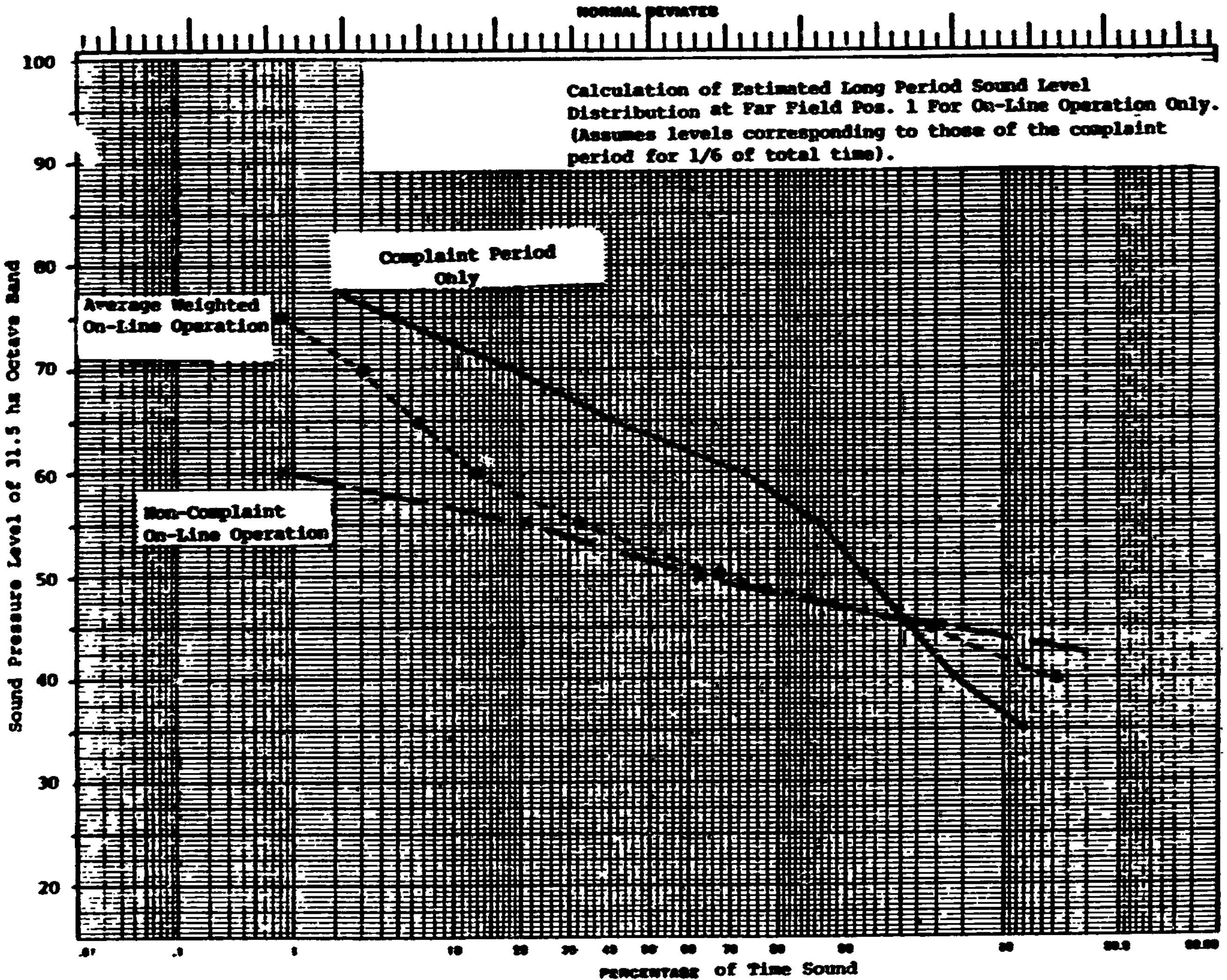

NORMAL DEVIATES
100
90
80
70
60
50
40
30
20
Sound Pressure Level of 31.5 hz Octave Band
Near Field Sound Levels. (Position 1, 269 feet from center of tower)
On-Line Operation Only
Minimum Ambient
.01
.1
1
10
20
30
40
50
60
70
80
90
99
99.9
99.99
PERCENTAGE of Time Sound Exceeded Specified Levels

FIGURE 5.3.2-6



Calculation of Estimated Long Period Sound Level Distribution at Far Field Pos. 1 For On-Line Operation Only. (Assumes levels corresponding to those of the complaint period for 1/6 of total time).

FIGURE 5.3.2-7

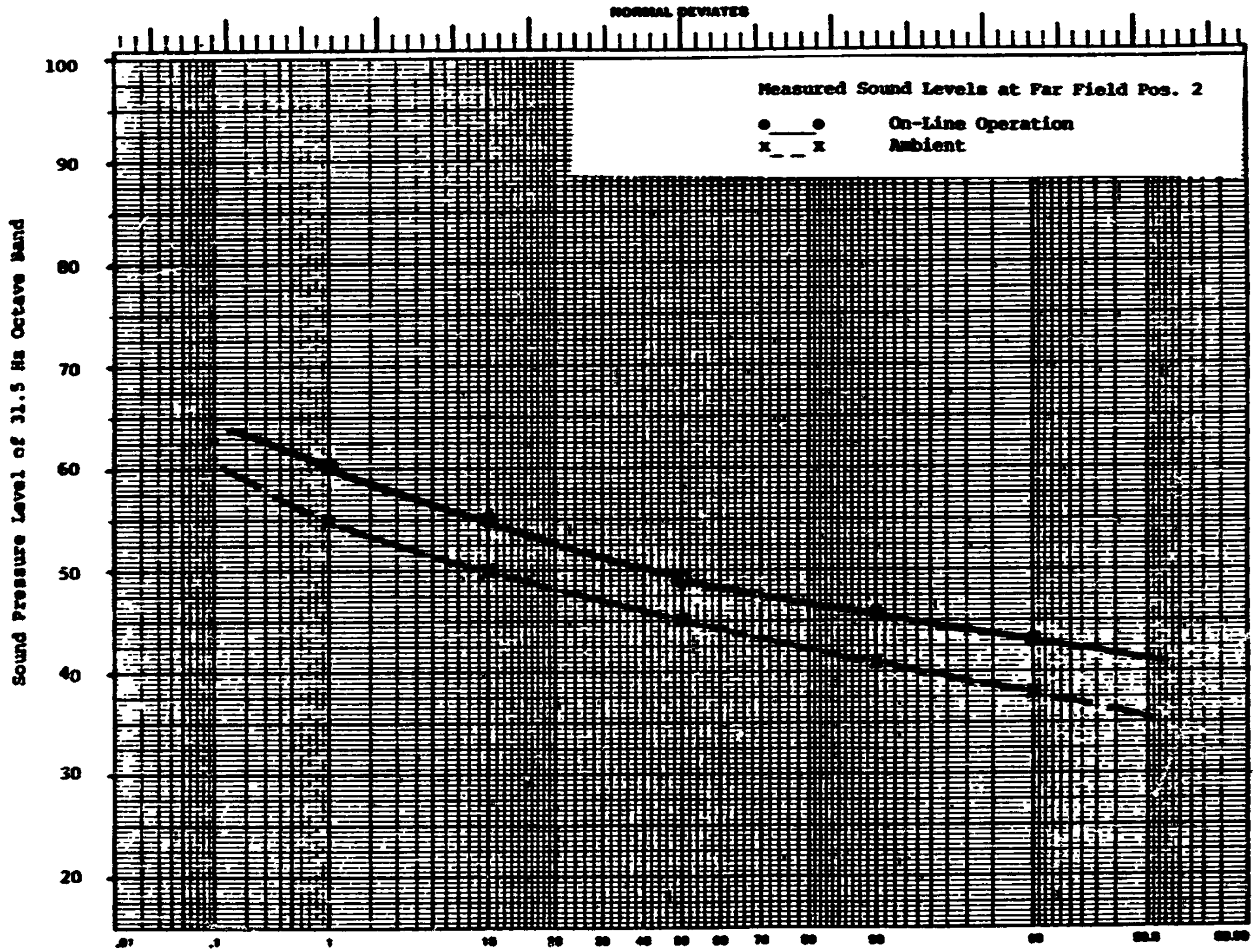

NORMAL DEVIATES
Measured Sound Levels at Far Field Pos. 2
●____● On-Line Operation
x_ _ x Ambient
Sound Pressure Level of 31.5 Hz Octave Band
100
90
80
70
60
50
40
30
20
.01
.1
1
10
20
30
40
50
60
70
80
90
99
99.9
99.99
PERCENTAGE of Time Sound
Exceeded Specific Levels

FIGURE 5.3.2-8

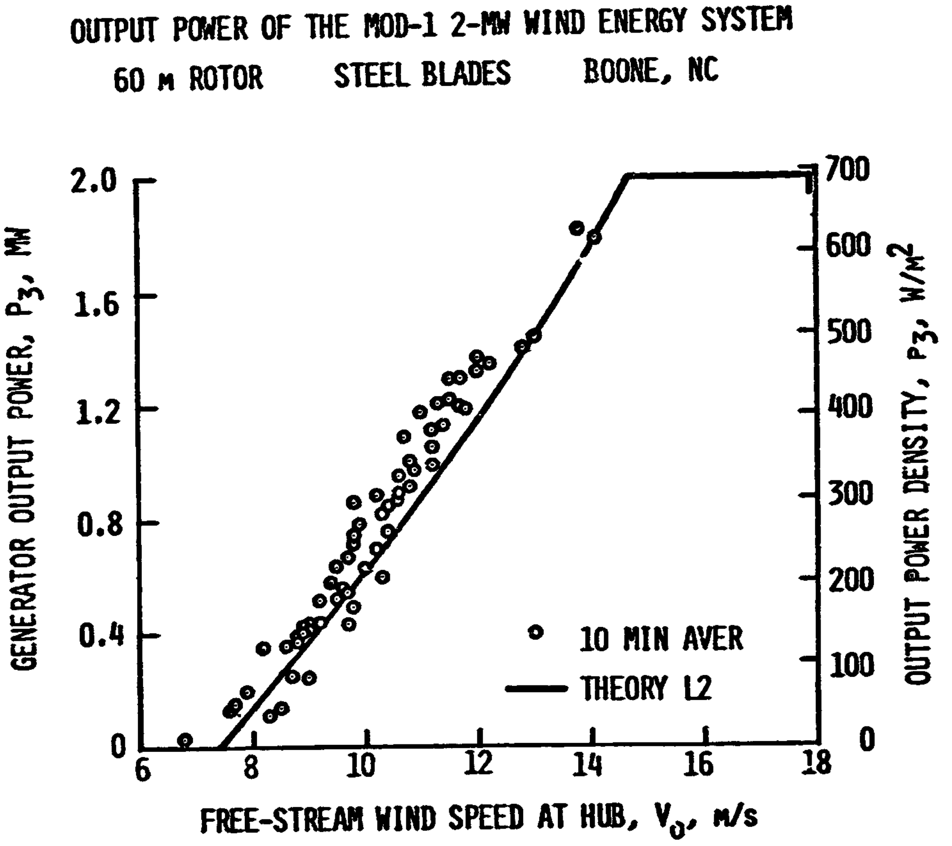

OUTPUT POWER OF THE MOD-1 2-MW WIND ENERGY SYSTEM
60 m ROTOR STEEL BLADES BOONE, NC
GENERATOR OUTPUT POWER, P_3, MW
2.0
1.6
1.2
0.8
0.4
0
OUTPUT POWER DENSITY, p_3, W/m^2
700
600
500
400
300
200
100
0
6
8
10
12
14
16
18
FREE-STREAM WIND SPEED AT HUB, V_0, m/s
10 MIN AVER
THEORY L2

Figure 5.4-1

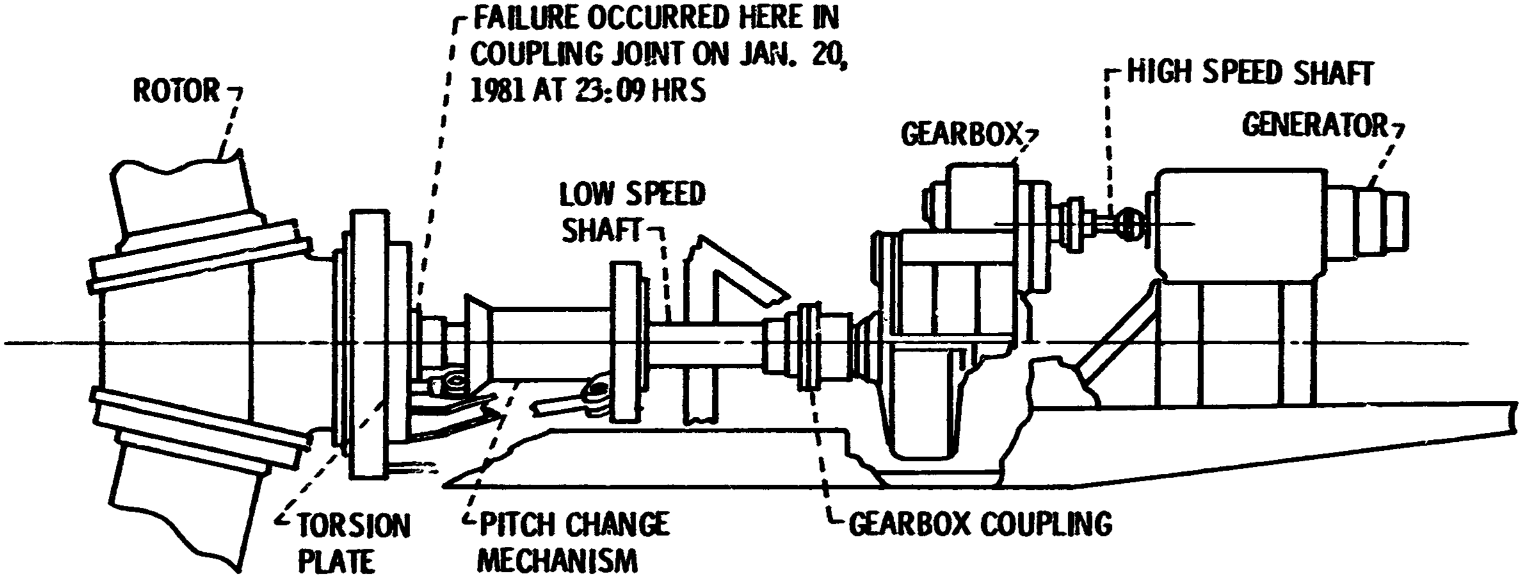


Figure 5.5.2-1. - Mod 1 drive train.

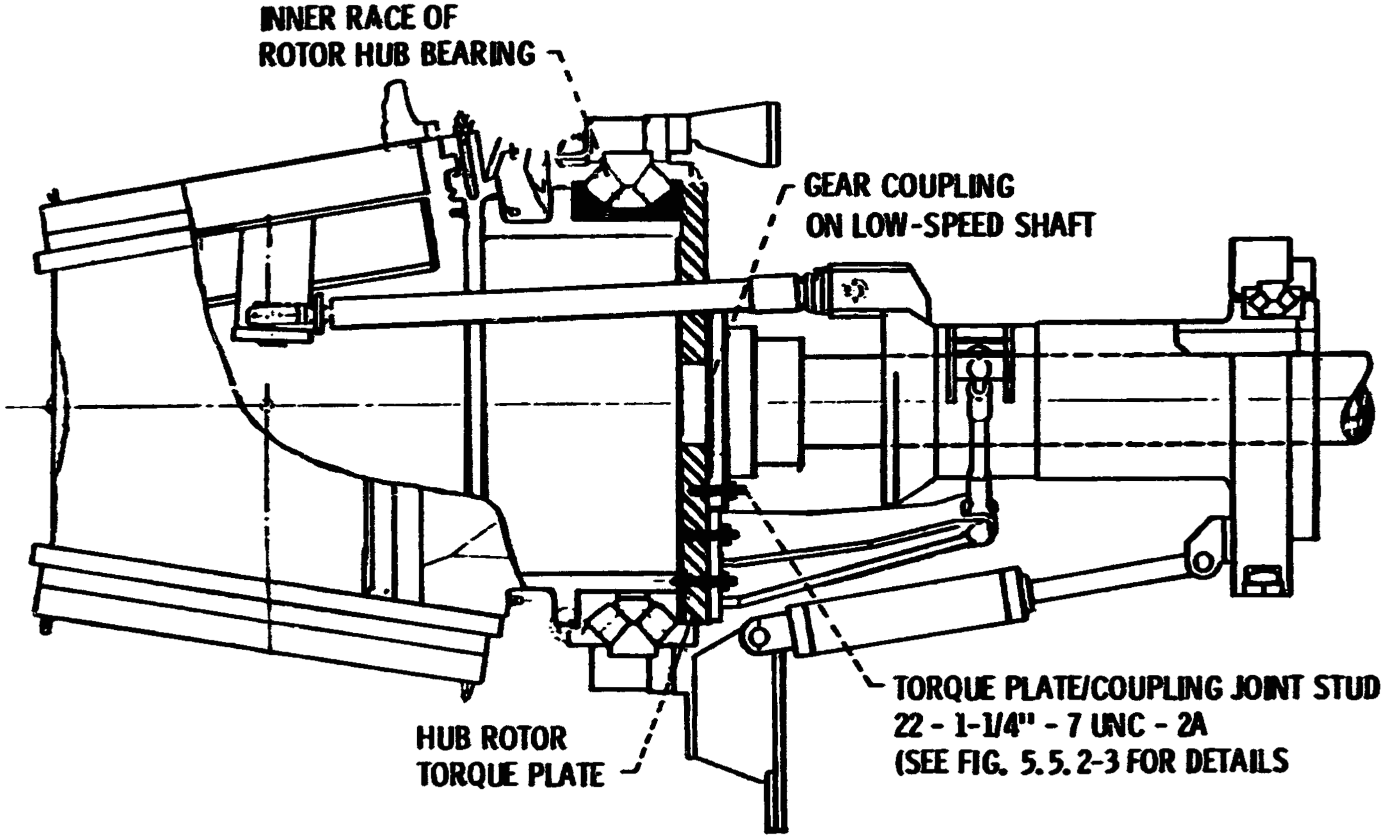


Figure 5.5.2-2. - Section view of hub/shaft interface showing studs location.

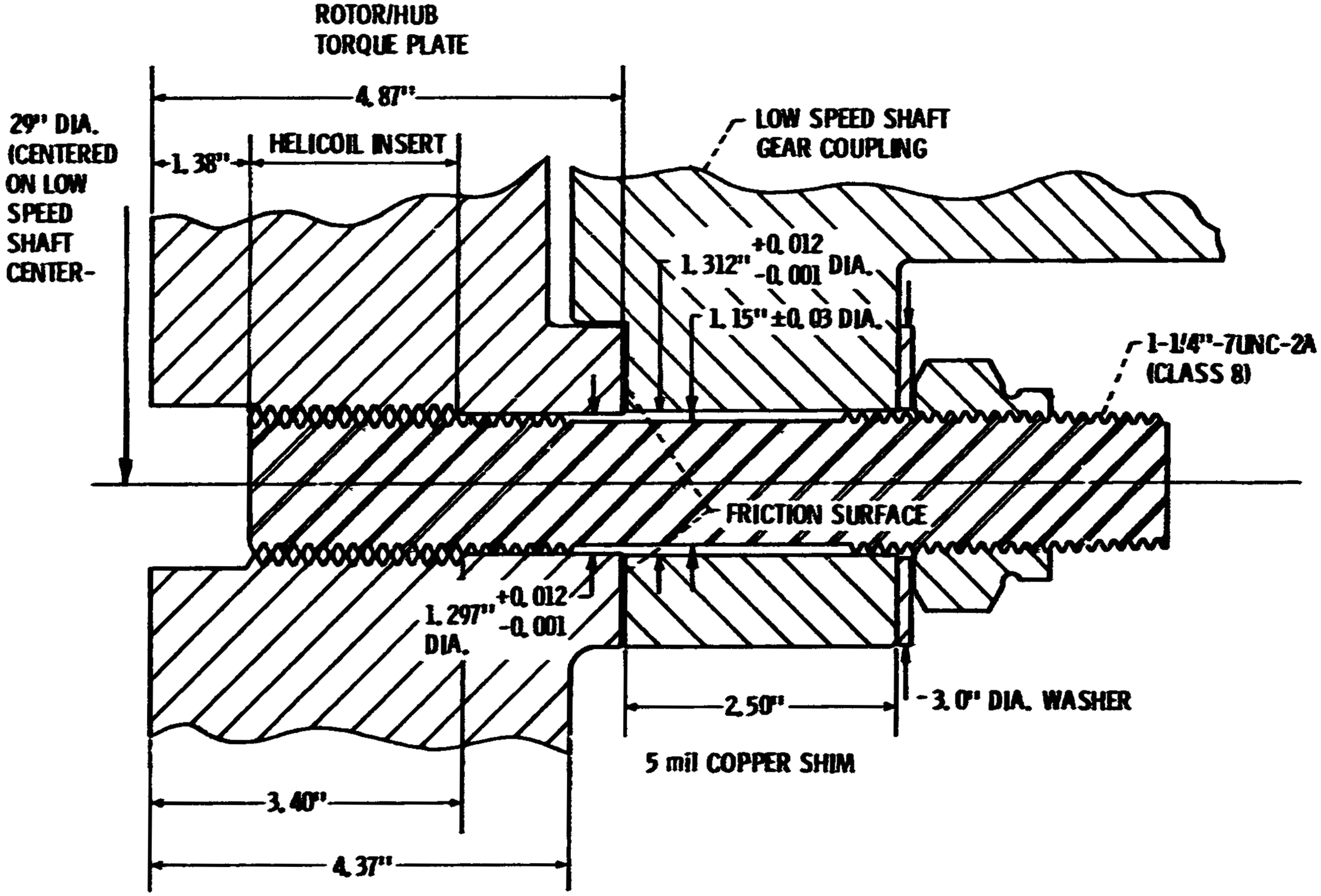


Figure 5.5.2-3. - Torque plate/coupling joint (stud detail).

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Rotor	
Number of blades	2
Diameter, ft	200
Speed, rpm	35
Direction of rotation	Counterclockwise (looking upwind)
Location relative to tower	Downwind
Type of hub	Rigid
Method of power regulation	Variable pitch
Cone angle, deg	9
Tilt angle, deg	0
Blade	
Length, ft	100
Material	Steel spar/ foam trailing edge
Weight, lb/blade	21,500
Airfoil	NACA 44XX
Twist, deg	11
Tip chord, ft	2.8
Root chord, ft	12
Chord taper	Linear
Tower	
Type	Pipe truss
Height, ft	131
Ground clearance, ft	40
Hub height, ft	140
Access	Hoist
Transmission	
Type	Three-stage conventional
Ratio	51
Rating, hp	2209
Generator	
Type	Synchronous ac
Rating, kVA	2225
Power factor	0.8
Voltage, V	4160 (three phase)
Speed, rpm	1800
Frequency, Hz	60
Orientation drive	
Type	Ring gear
Yaw rate, deg/sec	25
Yaw drive	Hydraulic
Control system	
Supervisory	Computer
Pitch actuator	Hydraulic
Performance	
Rated power, kW	2 000
Wind speed at 30 ft, mph:	
Cut-in	11
Rated	25.5
Cut-out	35
Maximum design	125

TABLE 4.1-1 - DESIGN SPECIFICATIONS FOR MOD-1 WIND TURBINE GENERATOR

	Weight, lb
Rotor assembly	
Hub	15,000
Blades	41,000
Bearings and structure	29,000
Pitch-change mechanism	11,000
Pitch-control hydraulics	12,000
	108,000
Nacelle assembly	
Bedplate	68,000
Fairing	5,000
Generator and exciter	14,000
Power generator equipment	1,000
Shafts, couplings, and clutch	18,000
Gearbox	58,000
Lubrication and hydraulic systems	4,000
Data acquisition system	1,000
Cables, lights, etc.	2,000
	171,000
Yaw assembly	
Bearing supports	47,000
Yaw brake	1,000
Yaw drive	8,000
	56,000
Tower assembly	
Structure	313,000
Elevator and miscellaneous	1,000
Cabling and conduit	6,000
	320,000
Total (excluding ground equipment)	655,000

TABLE 4.1-2 - WEIGHT BREAKDOWN OF MOD-1
WIND TURBINE GENERATOR

Function	Additional Restrictive Conditions
Pitch to Any Angle (±5°)	Wind Speed* 15 mph
Yaw to Any Angle (±5°)	Wind Speed* 35 mph
Yaw Hydraulics Pump Motor On/Off	-
Hub to Any Angle (±10°)	Wind Speed* 25 mph
PCM Pump Motor On/Off	-
Release/Apply Yaw Brake	Wind Speed* 25 mph
Main Lube Pump On/Off	-
Hub to Any Speed (±0.5 rpm)	Break Away Wind Speed* 25 mph

* Wind Speed measured at hub height

TABLE 5.2-1. Manual Functions

Function	Description
Monitor Enable	Process Lockout Sensors, Initialize Commands
Initialization	Initialize Yaw, Pitch, and Lube Subsystems
Site Enable	Process Automatic Restart Sensors
Anti-Stall	Limit β as a $f(V_W)$ to Prevent "Stall"
Overstress	Limit Structural Stress as a $f(V_W$, Yaw Error)
Yaw Correct	Align Nacelle With Wind Vector
Pitch Ramp	Ramp β 90° to 72° - Maximum Coefficient of Lift
Speed Ramp	Ramp Generator Speed 0 to 1200 rpm
Rate Sync	Set Freq. Generator = Freq. Utility
Voltage Sync	Set Voltage Generator = Voltage Utility
Angle Sync	Enable Switch Gear Synchronizer, Wait for Breaker Close
Power Ramp	Step Power in 25 kW Increments 2 Sec. Apart
Shutdown	Disengage Utility, Feather Blades, Brake, Park Rotor
Power Peaking	Iterate Power Set - Point to Max. Value for $11 \leq V_W \leq 24.6$

Table 5.2-2. Control System Functions

Mode	Functional Description	Operating Conditions	
		Control Parameters	Wind Speed (mph)
Startup	Ramp Blade Pitch Angle to +72° With Shaft Brake On. Accelerate Rotor to Rated Speed by Pitching Blade Using Speed Schedule after releasing the brake.	● Time ● Shaft Speed ● Blade Angle	11 to 35
Rate Sync	Closed Loop Control of Pitch to Make f Utility = f Generator	● Utility Frequency ● Generator Speed	11 to 35
Angle Sync	Closed Loop Control of Pitch to Make Ø Utility = Ø Generator	● Utility Phase Angle ● Generator Phase Angle	11 to 35
Power Control	CPU Ramps Power Reference Command to Set Desired Power Output	● Time ● Generator Power ● Blade Angle	11 to 35
Manual	For Testing and Periodic "exercising," the Blade can be commanded Over the Full Range.	● Manual ● Blade Angle ● Time	0 to 25
Pitch Jam	"Pitch Jam" Status to NMU if Pitch Mechanism does not Respond to Position Control	● Time ● Voltage	Any
Power Down	CPU Ramps Reference to Zero Power	● Time ● Generator Power ● Blade Angle	11 to 35
Slow Down	Reduce Rotor Shaft Speed to 1 rpm by Slewing Blade at 1 Deg/Sec	● Blade Angle ● Shaft Speed	Any

Table 5.2-3. Pitch Control Modes of Operation

Wind Speed (mph)	Drive	Brake	Notes
0 to Cut-In	"Off"	"On"	No operation
CI to Cut-Out	Corrects for Yaw error of 5° for 5 minutes	"Off" when not rotating. "On" if RPM above 8 at lower pressure	0.25 deg/sec
Above CO	"OFF"	"On"	Shutdown
0 to Rated	Manual - to any angle	Manual	For Test

Table 5.2-4. Yaw Control

Type of Shutdown	Contract System Functions	Criteria for Shutdown
Normal	1. Yaw Off if Failure 2. Power Down (Pitch Change) 3. Breaker Open 4. Slow Down (Speed Kamp) 5. Rotor Stop 6. Apply Parking Brake	Manual Command Dispatcher Command Wind Speed Drops Below 11 MPH User Subsystem Failure Wind Speed - Yaw Error Out of Band Temperatures Out of Band Average Wind Speed Above 35 MPH Emergency Pitch Hydraulic Pressure Low
Emergency	1. Yaw Off if Failure 2. Pitch Emergency Feather 3. Breaker Open 4. Rotor Stop 5. Apply Parking Brake	Frequency Out of Band Shaft Speed too High Main Breaker Open while in Gen Utility Voltage LDip Below Limit Wind Speed-Yaw Error Out of Band Any Vibration Above Limit Data Link Anomoly
Utility Outage	Emergency Feather, Yaw Motor Off, Brake On, Shaft Brake Off	Utility Voltage Drops Out
Pitch Jam	1. Emergency Feather 2. Yaw 90° to Wind & Track	Blade Will Not Respond

Table 5.2-5. Shutdown Logic

TABLE 5.3.1-1 - TV CHANNELS AVAILABLE IN BOONE

Channel	Station Location	Network Affil.	Effec. rad. visual power (kW)	Antenna Location Latitude	Antenna Location Longitude	Distance from WT (in km)	Direction to Trans. (deg. from N)
2(a)	Sneedville, TN	ABC	100	36°22'52"	83°10'48"	134	278
2(b)	Greensboro, NC	CBS	100	35°52'13"	79°50'25"	170	103
3	Charlotte, NC	CBS	100	35°17'50"	81°6'53"	116	154
5	Bristol, VA	NBC	85.1	36°26'57"	82°6'31"	46	302
7	Spartanburg, SC	CBS	294.4	35°10'12"	82°17'26"	130	205
8	High Point, NC	None	316	35°48'47"	79°50'36"	171	105
9	Charlotte, NC	ABC	316	35°15'41"	80°43'38"	138	141
11	Johnson City, TN	CBS	245	36°25'55"	82°8'15"	47	299
12	Winston-Salem, NC	NBC	316	36°22'31"	80°22'27"	118	82

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