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DESIGN AND OPERATING EXPERIENCE ON THE U.S. DEPARTMENT OF ENERGY EXPERIMENTAL MOD-0 100-kW WIND TURBINE

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ABSTRACT

The Mod-0 100 kW Experimental Wind Turbine was designed and fabricated by NASA, as part of the Federal Wind Energy Program, to assess technology requirements and engineering problems of large wind turbines. The machine became operational in October 1975 and has demonstrated successful operation in all of its design modes. During the course of its operations the machine has generated a wealth of experimental data and has served as a prototype developmental test bed for the Mod-0A operational wind turbines which are currently used on utility networks. This paper describes the mechanical and control systems as they evolved in operational tests and describes some of the experience with various systems in the downwind rotor configuration.

THE MOD-0 100 kW EXPERIMENTAL WIND TURBINE is a part of the Federal Wind Energy Program under the direction of the U.S. Department of Energy. The NASA Lewis Research Center has designed, built and erected this machine near Sandusky, Ohio and is currently testing it to obtain engineering data on large horizontal axis wind turbines.

The wind turbine described in a previous report (1)* has a 38 m (125 ft) diameter two-bladed rotor which drives a 125 KVA synchronous generator through a step up gear box. The rotor is positioned downwind of a 30 m(100-ft) steel truss tower as pictured in fig. 1. The rotor is designed to operate at a constant speed of 40 rpm and it drives a 480 V 60 Hz three phase generator at 1800 rpm. Rotor speed or output power level is maintained by controlling rotor blade pitch angle with an active feedback control system. The rotor, generator, transmission and associated equipment are mounted in a nacelle, fig. 2, which can be yawed to align the rotor with the wind and power, instrumentation and control connections to the ground are made through slip rings.

The turbine was designed to begin generating power in winds of 16 km/hr (10 mph) and produce 100 kW at a wind velocity of 29 km/hr (18 mph). In winds above 29 km/hr, the generator continues to operate at 100 kW output by adjusting the pitch of the rotor blades to spill excess wind energy. When the wind velocity exceeds 48 km/hr (30 mph) or drops below 13 km/hr (8 mph) the generator is taken out of synchronism with the power network, the blades are feathered to bring the rotor to a halt and the machine is shut down to await the return of winds in the proper velocity range. The high wind speed limit is set by structural limits of the rotor. The low wind limit is set to keep the wind turbine from drawing utility power to maintain rotor speed. Initially the Mod-0 was designed to operate in winds between 64 km/hr, (40 mph) and 13 km/hr (8 mph) but rotor loads encountered in winds above 48 km/hr (30 mph) made it necessary to limit wind maximum wind velocity to 48 km/hr. The follow on Mod-0A operational wind turbines were built with added strength in the rotor and operate in winds between 13 and 64 km/hr, (8 and 40 mph).

Final assembly of the machine was completed in September 1975 and since that time successful operation of the wind turbine has been demonstrated for each of its design operating modes at 40 rpm: manual operation on a resistive load, synchronized to a large power grid and a small power grid, and unattended automatic synchronization and operation on a large power grid.

This paper presents a brief description of the wind turbine mechanical systems and, in somewhat more detail, the control systems which are used in manual and automatic operation of the machine. Operational experience with regard to the pitch controller is discussed and the problems encountered before a satisfactory yaw drive scheme was defined are recounted in some detail.

MOD-0 WIND TURBINE DESIGN

The Mod-0 wind turbine design is presented in this paper in two categories, mechanical design and control system design. The designs are presented as they have evolved over 2 1/2 years of operational experience and those items in the mechanical system which required modification from the original design are emphasized. The control systems also were designed or modified as operational and test experience was gained and are discussed in greater detail than the mechanical system which has been presented in other sources (1).

MECHANICAL SYSTEM - The wind turbine nacelle is depicted in fig. 2 and consists of a two-bladed rotor, a low speed shaft which supports the rotor

*Numbers in parentheses designate references at end of paper.

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and drives a generator through a 45 to 1 step up gear box and "V" belts. The wind turbine generates 100 kW of electric power at a wind speed of 29 km/hr. Rotor power is controlled by an active control system which changes rotor blade pitch by means of hydraulic actuators. The system permits collective pitch changes only. Hydraulic power is supplied from a system mounted in the nacelle and is delivered to the hub through the low speed shaft. Alignment with the wind is maintained by redundant yaw motors through a double reduction self locking worm drive engaging a bull gear attached to the nacelle.

Since the Mod-O was first put into operation in October 1975, some changes in the mechanical details of the nacelle have been incorporated and are depicted in the cutaway drawing. These changes include the fluid coupling on the high speed (1800 rpm) shaft, the dual yaw drive and the yaw brake. The fluid coupling is installed to introduce damping into the drive train. Slip can be varied by adjusting the level of fluid making it an ideal device for an experimental program. The dual yaw drive was added to provide more stiffness to the yaw drive and to eliminate the free play in yaw that is present in the single yaw drive system. The yaw brake was added by placing a large disk between the yaw drive gear and the nacelle and spacing three brake calipers around the circumference of the support cone. Aside from these changes the Mod-O wind turbine mechanical system essentially corresponds to the original design. The design changes and the reasons for incorporating the changes are discussed more fully later in this paper under the Operational Experience Section.

CONTROL SYSTEMS - The Mod-O wind turbine is designed to be a fully automatic piece of power production equipment for use on a utility grid. In order to meet these requirements the control system had to be capable of monitoring wind conditions, maintaining alignment with the wind, controlling rotor speed and power level, starting, synchronizing, and stopping the wind turbine safely, monitoring key parameters throughout to assure that critical items are operating within specified tolerances, and providing a remote operator (typically a power dispatcher) the capability of starting and stopping the machine. Five control systems were provided on Mod-O to accomplish these tasks:

1. The rotor blade pitch controller which adjusts blade pitch to control rotor speed or alternator output power.

2. The yaw system which keeps the wind turbine aligned with the wind.

3. The microprocessor which controls the automatic operation of the wind turbine including startup, synchronization and shutdown.

4. The safety system which monitors system operation and provides a wind turbine shutdown signal when out of tolerance performance is detected.

5. The remote control and monitor system which provides a remote operator with the ability to enable the microprocessor to start or stop the wind turbine and to monitor machine performance.

A block diagram depicting the interactions of the control systems is shown in fig. 3. The five control functions operate nearly independently and are interfaced to each other through the microprocessor.

PITCH CONTROLLER - Wind turbine rotor power is a function of wind speed and blade pitch angle. Therefore, either rotor speed or rotor power at a given rotor speed can be controlled by adjusting blade pitch angle. The relationship between rotor power and blade pitch angle for the Mod-O turbine at 40 rpm is given in figs. 4 and 5.

The Mod-O pitch controller operates to maintain either rotor speed or rotor power by means of a hydraulically actuated blade pitch mechanism which is activated by a closed loop servo system. The servo controller operates in three modes; closed loop control to regulate speed; closed loop control to regulate power output; and pitch angle position control used at low rotor rpm where speed control is ineffective, see below. A block diagram of the pitch controller is shown in fig. 6. As indicated in the figure, speed and power are controlled with a simple proportional plus integral control function.

The pitch controller is programmed to increase blade pitch angle to increase rotor power and decrease the angle to reduce power. The pitch angle limit is set at 0° to avoid the region of stall that occurs in low winds, fig. 5. The wind speed limit of 48 km/hr (30 mph) is set by the structural limits of the machine, and the power limit is set by the drive train and generator design.

In a typical operation cycle the wind turbine is started by ramping (i.e., linear increase as a function of time) blade angle using position control until a 5 rpm rotor speed is obtained. Above 5 rpm closed loop speed control is used to increase rotor speed to 40 rpm by ramping the speed set point. The 40 rpm speed is maintained while the automatic synchronizer connects the alternator with the power network. At this point the controller is switched to the power control mode and the set point is advanced to 100 kW. The rotor speed is maintained at 40 rpm by the synchronous torque of the power network. At shutdown, blade pitch angle is reduced until a zero power output is achieved at which point the alternator is disconnected from the network, blade pitch angle decrease is continued until the rotor is brought to a halt and the blades are feathered at an angle of -90°. The rotor blades are left at this angle until a startup command is received.

YAW CONTROLLER - The yaw controller is used to keep the wind turbine aligned with the wind. The system is powered by two redundant yaw motors electrically paralleled and mechanically coupled to share the load. The motors drive two double reduction worm drive gear boxes connected to the nacelle bull gear by pinnion gears. The yaw drive system drives the nacelle at a constant speed of 1°/sec, a rate which was set to limit rotor loads induced by the gyroscopic effects of yawing. The dual yaw drive and yaw brake is depicted in fig. 2 and are discussed later in the paper. The features of the yaw controller will be discussed here.

The yaw controller senses directional error from a wind vane mounted on the nacelle, fig. 2, which measures the apparent wind direction relative to the nacelle, a direct measure of yaw error. The wind vane signal is filtered by a 30 second time constant filter to eliminate noise and to smooth out transient wind shifts. The controller has a dead band of ±25° which must be exceeded for several seconds, due to the filtering, before a correction is initiated. Once activated, the yaw motors remain on until the filtered yaw error signal is within ±18°.

The yaw control system as originally configured was more responsive to yaw errors than the system described above. Initially the controller had a permissable error band of ±15° and passed the signal through a 15 second filter. This system was found to be responding to high frequency variation in wind direction, as indicated by the nacelle wind vane, which created almost constant operation of the yaw motors with little or no effect on the pointing accuracy of the wind turbine. When the limits were opened up the yaw motors were found to operate typically less than five times per hour with no adverse effects on the pointing accuracy.

A yaw brake is provided to restrain the nacelle in yaw, fig. 2. The brake is used as a passive restraining frictional force in yaw. The brake system is pressurized to a constant pressure and is left on throughout for operating and nonoperating conditions. The yaw brake is discussed in greater detail below under Operating Experience.

For automatic operation of the wind turbine the yaw controller is operative whenever the wind velocity is above 13 km/hr (8 mph), and is disarmed in lower wind velocities.

THE MICROPROCESSOR - The microprocessor is the control unit which permits unattended automatic operation of the wind turbine to take place. The unit provides the commands to initiate the startup, control the normal operation, and shutdown the wind turbine based on wind conditions. Once the microprocessor has been activated no other function is required of an operator unless he wants to shut down the wind turbine and/or disable the microprocessor.

Once enabled the microprocessor monitors the wind and initiates a startup sequence fig. 7, when the wind speed exceeds 21 km/hr (13 mph). During the startup sequence, the pitch hydraulic system is started and after the pressure builds up the rotor blades are pitched at a rate of 36° per minute toward the power position. When the rotor speed is greater than 5 rpm the pitch controller is switched to speed control and the speed set point is increased at the rate of 15 rpm/minute to synchronous speed. Just below synchronous speed the alternator field is activated, and at 40 rpm the automatic synchronizer is enabled. After the alternator is connected to the power grid, the pitch controller is switched to the power control mode and the set point is advanced to 100 kW which completes the startup mode.

The shutdown sequence is also automatic and can be initiated by an operator command, wind conditions, the safety system, or several checkpoints in the microprocessor program. The shutdown sequence is shown in fig. 8. Upon receiving a stop command, the microprocessor switches the pitch controller to the pitch control mode. The blade pitch angle is then reduced at the rate of 30° per minute until the power output is zero. The alternator is then disconnected from the line and the field is turned off. When the blades are fully feathered the pitch hydraulic system is turned off.

If the shutdown is initiated by an unacceptable wind speed, the wind turbine will start automatically when the wind speed returns to within acceptable boundaries. Although startup requires a wind speed greater than 21 km/hr (13 mph), shutdown is not initiated until the wind drops below 13 km/hr (8 mph), which reduces the startup-shutdown cycles in light variable winds. Similarly, shutdown is initiated by winds above 48 km/hr (30 mph) and restart is not initiated until the wind velocity drops below 40 km/hr (25 mph). The wind speed signal to the microprocessor is filtered through a 1 minute filter to further reduce unnecessary cycling.

The microprocessor will also initiate a shutdown sequence on command by the operator; whenever an abnormality is detected by the microprocessor; or on a signal from the safety system. Abnormalities detected by the microprocessor include: Slow startup or synchronization, loss of hydraulic pressure, loss of synchronization, and microprocessor failure. Each of these conditions initiates a wind turbine shutdown and requires an on site reset before the wind turbine can be restarted.

A description of the Mod-0 microprocessor hardware, program development and operational experience is presented in Ref. 2.

SAFETY SYSTEM - The concept of unattended operation dictates that a protective system monitor the wind turbine and effect a safe shutdown if a malfunction or out of tolerance performance is detected. The system must be reliable to prevent unnecessary shutdowns but must incorporate redundancy and failsafe designs to insure adequate protection.

The safety system developed for the Mod-0 wind turbine incorporating these features is shown in a block diagram in fig. 9. The system includes a series of primary sensors connected to an interface/annunciator circuit. The annunciator is provided to allow a rapid determination of the cause of shutdown. The annunciator function, condensed, is also transmitted to the remote control and monitoring station described below. The output of the interface circuitry controls a relay logic system, interconnected with the wind turbine electrical system, which effects the shutdown.

A second set of sensors is used as a redundant but not complete error detection shutdown system. In this system, an independent path is used to effect the shutdown and errors detected in the wind turbine nacelle effect a shutdown by switching nacelle wiring directly without running signals to the control room and back to the nacelle as is done in the primary system. The safety system is functionally independent of the data and control systems and provides a positive override in the event of a detected failure.

Safety system primary sensors are listed below:

<u>Temperature sensing</u>. - Low speed shaft bearings (2); high speed shaft bearing; gear box; alternator; pitch hydraulic fluid; pitch hydraulic pump motor.

<u>Vibration</u>. - Low speed shaft bearing (rotor).

<u>Pneumatic pressure</u>. - Emergency feather gas bottle.

<u>Hydraulic pressure</u>. - Pitch hydraulic pressure; yaw brake pressure.

<u>Hydraulic level</u>. - Pitch hydraulic; yaw hydraulic.

<u>Yaw error</u>. - (Nacelle relative wind angle)

<u>Electrical</u>. - Overcurrent; instantaneous trip; time overcurrent trip; reverse power - alternator.

<u>Rotor overspeed</u>. - 42 rpm.

<u>Microprocessor</u>. - Cycle timer reset by microprocessor software.

An error from any of these sensors will cause an emergency shutdown. In an emergency shutdown, a valve in the pitch hydraulic system is opened which drives the rotor blades to the feather position at a fixed rate of 30° per minute. This procedure is referred to as an emergency feather of the rotor. Two seconds after the emergency feather is initiated, the field contractor, and the synchronizing contractor are opened. The 2-second delay is provided to insure that the blades are feathered enough to prevent overspeeding when the electrical load is removed from the rotor. Additionally, the microprocessor is given a halt command which instructs it to shutdown the machine.

The redundant system is intended as a backup to insure safety in the event of a failure in the primary system. The sensor list is not as extensive, but generally duplicates the primary system, using separate sensors and wiring throughout. The following are redundant sensors: Vibration, low speed shaft (rotor); Yaw error, nacelle/weather tower difference; Electrical, overcurrent, reverse power (alternator); Pneumatic pressure, emergency feather gas bottle, rotor brake gas bottle; Overspeed, high speed shaft.

Yaw error and overcurrent shutdowns commanded by the redundant safety system are identical to the primary system shutdown except that the microprocessor is not directly halted, and completely independent wiring is used. Vibration and pneumatic pressure sensors cause only an emergency feather, and overspeed to 45 rpm causes emergency feather and rotor brake application. The redundant system is designed as a backup, therefore the sensors are set to trip at slightly larger errors. A redundant shutdown causing only emergency feather, i.e., vibration or pressure, will cause a complete emergency shutdown because the overcurrent sensor will desynchronize the machine when the rotor blade angle has been reduced enough to produce negative load on the generator tripping the overcurrent sensor. In this event the machine shutdown is completed by the safety system directly rather than depending on the microprocessor to complete this function as is done in a primary system shutdown.

REMOTE CONTROL AND MONITOR SYSTEM - The Remote Control and Monitor System (RCMS) provides the interface between the wind turbine and the power dispatcher's control room. The RCMS serves as a control link, status indicator, and performance monitor, and is connected to the wind turbine by a pair of telephone wires. A single unit is capable of controlling a number of wind turbines. The RCMS control panel is shown in fig. 10.

The system is capable of two control functions or on-off command pulses: (a) startup and shutdown of the wind turbine through the microprocessor and, (b) initiation of an emergency shutdown of the wind turbine. The startup command enables the microprocessor which takes control of the wind turbine. The shutdown command tells the microprocessor to shut down and deactivate the wind turbine. After this command has been sent the power dispatcher must send a startup command before the wind turbine will begin another startup sequence. The emergency shutdown command is set directly to the safety system and is provided as a backup to the normal shutdown command through the microprocessor. However, if the wind turbine is halted by the emergency shutdown signal, an operator must reset the safety system at the wind turbine site before the machine can be restarted.

The status indicators show machine conditions, blades feathered and automatic or manual operation, and 6 possible error conditions detected by the safety systems: overspeed, yaw error, temperature, overcurrent or reverse power, vibration, and hydraulic or pneumatic systems failure. Additionally, the status of the microprocessor is indicated on the control function panel.

Performance of the machine can be monitored through an analog data section. Four channels of data are displayed in digital format: wind speed, rotor speed, power and VARS or reactive power. Any two channels can be monitored simultaneously, with the readouts scaled in engineering units.

OPERATIONAL EXPERIENCE

Since the Mod-O wind turbine was dedicated in October 1975, operational techniques have been developed and much technical data has been obtained and reported to the wind turbine community. The items reported herein were chosen either to demonstrate the design evolution of the Mod-O wind turbine or because of the current interest expressed in the particular subject matter by the wind turbine community.

YAW DRIVE EXPERIENCE - Wind turbines having two blades have often experienced difficulties in some phase of their development from the oscillatory forces induced by the two bladed rotor. The forces arise because the two bladed rotor is not polar symmetric and large changes in moment of inertia occur about the vertical axis as the rotor turns through 360°. The condition is aggravated when the nacelle azimuth is changed to maintain alignment with the wind or the nacelle is disturbed in yaw by external forces such as changes in wind direction or velocity.

The Mod-O yaw drive experience presents the steps taken to deal with yaw drive problems, including unsuccessful attempts and the final design which produced satisfactory operation of the wind turbine. The design evolution included a single yaw drive and a dual yaw drive with a yaw brake. Tests were also run using a free yaw system (i.e., yaw drive disconnected from the nacelle) with the yaw brake providing a restraining force.

SINGLE YAW DRIVE - The Mod-O wind turbine was designed with a positive yaw drive driven by redundant 10 hp electric motors. Nacelle azimuth was maintained and altered by a self-locking double reduction worm gear driving a pinion which engages a bull gear attached to the nacelle, as depicted in fig. 2. Initial tests of this system were discussed in ref. 3. The yaw drive system as initially installed had two problems, first free play in the mechanism permitted yawing motion to occur and second, the stiffness of the mechanism resulted in a nacelle yawing resonant frequency very near to twice the rotor speed, "2P," a frequency at which there is a significant driving force available on a two-bladed machine. The free play, the resonant frequency, and the small drag afforded by the friction in the yaw bearing came together to produce a problem characterized by nacelle yawing motion and high rotor loads, including the blades and the low speed shaft which supports the rotor.

The dual yaw drive was installed to alleviate this problem by raising the yawing frequency above the "2P" point to 2.5 P and eliminating free play by preloading one drive shaft against the other. A yaw brake was installed as a backup system to be used for additional yaw restraint in case this was needed. The revised yaw drive and brake is depicted in fig. 2.

DUAL YAW DRIVE - Initial tests with the dual drive system indicated that the purely elastic restraint in yaw was unsatisfactory. High yaw response with attendant excessive rotor loads were again experienced in gusty winds above 30 km/hr and the yaw brake was employed to provide additional restraint. The yaw brake was used to lock the nacelle to the tower during normal operation and to provide a drag force or damping when yaw adjustments were being made by the yaw drive. This required a two stage pressure system for the yaw brake, a locking pressure and a somewhat lower drag pressure. First operation with this system was tried with a 36 700 N-m drag force on the nacelle during yawing operations (27 500 ft-lb), and this was found to be too low to prevent high amplitude yaw motion during yawing operations. The drag force was increased to 100 000 N-m and the increased damping reduced the motion and loads to within acceptable levels. This two stage pressure brake system was found to be satisfactory and was used on the Mod-0 and Mod-0A wind turbines.

Two additional tests have been conducted on the Mod-0 wind turbine yaw system which have yielded promising results. In the interest of simplifying the yaw brake system, tests were run in which the preload was removed from the yaw drive mechanism and the nacelle was allowed the normal free play in yaw built into the system. The yaw brake was used as a passive restraining force in these tests supplying a damping force when the yaw motors were off and a drag force when an azimuth change was being made. Tests with this system at various brake pressures have been completed and the results are being evaluated at this time. However, we have concluded at this point that the passive brake system with a single pressure is at least as good as the active two stage pressure system in providing the yaw restraint necessary to keep rotor loads within acceptable limits, while greatly simplifying the yaw brake system.

FREE YAW - Tests have been conducted on the Mod-0 wind turbine in passive or free yaw. The tests were inspired by suggestions by K. Hohenemser (4) among others and were conducted with the yaw drive disconnected and the nacelle free of any positive yaw drive. During these tests the yaw brake was used as a safety device and could be controlled from the wind turbine control room to provide yaw restraint should any instabilities occur.

Tests with the wind turbine in free yaw indicated that the system was at least neutrally stable in yaw while operating at 40 rpm and synchronized to a utility grid with no drag from the brake. A tendency did exist for the machine to wander or oscillate in yaw at a very low frequency under free yaw conditions as indicated in fig. 11. However, the application of the yaw brake stabilized the nacelle in yaw and produced satisfactory operation. The nacelle yawed out of the wind to angles as high at 50° and returned during the tests. The nacelle yaw angle was biased to the positive side during normal operation when the turbine was producing power and biased to the negative side when the turbine was motored in low winds. The yaw angle error data is presented in fig. 11 which also shows the effect of yaw brake restraint in stabilizing the nacelle in yaw. Rotor loads were excessive when the nacelle was allowed to wander or oscillate, unrestrained by the yaw brake. Yawing rates of 5° per second were sometimes reached and high rotor loads accompanied these conditions. (The design yaw rate with the yaw drive is 1° per sec.) The application of the yaw brake eliminated the high yaw rates and appears to permit the nacelle to make yaw corrections to maintain alignment with the wind as indicated in the figure.

Tests were also conducted in the free yaw condition to determine if the wind turbine would align itself with the wind during nonoperating or shutdown conditions. In shutdown the wind turbine blades are feathered, i.e., blade pitch angle is -90° compared to 0° for full power, the rotor is free to rotate and the yaw brake is released. It was demonstrated that the wind turbine in this shutdown condition would reorient itself into the wind from any yaw error including 180° in less than a minute in winds above 13 km/hr (8 mph). This is faster than the same maneuver can be accomplished by the active yaw drive. Tests have also indicated that the machine remains in alignment with the wind in winds above 13 km/hr which is compatible with our startup wind speed of 21 km/hr (13 mph).

The free yaw test results are presently being analyzed as are the passive yaw brake results and will be the subject of a more detailed treatment at a later date. However, we felt that the results are of significant interest to the wind turbine community and should be presented in this preliminary form.

POWER CONTROLLER OPERATING EXPERIENCE - The Mod-0 design did not include the fluid coupling indicated in the cutaway drawing, fig. 2. The original design called for a rigid steel shaft between the step up gear box and the "V" belt sheave bearing support. Initial tests with this design in synchronous operation showed the power control to be unstable when proportional control was added to the system and operation in high gusty winds created large variations in power level when only integral control was used. Power fluctuations as indicated in fig. 12 were encountered with this drive train configuration and attempts to increase control system response by increases in loop gain were limited by instabilities. The problem was caused by the presence of a lightly damped drive train vibration mode with a frequency very near the rotor speed, "1P," (5). Increases in loop gain made the system resonant at this frequency and lower gain settings did not provide adequate response to maintain control of power level during gusty, high wind conditions.

The fluid coupling provided a solution to this problem by adding damping to the drive train which permitted us not only to use proportional control but also enabled us to increase the overall loop gain to the point that effective control of power level can be assured in highly variable wind conditions. Figure 13 is an indication of the control system effectiveness. The present control system used in conjunction with the fluid coupling has demonstrated effective control of power level on the Mod-0 machine in highly variable wind conditions. The results of Mod-0 control system tests and analysis will be subject of a report to be released shortly.

CONCLUDING REMARKS

This paper has presented a brief description of the Mod-0 mechanical and control systems. Operational experience with the yaw drive and the power controller is also presented. As a result of the Mod-0 downwind rotor test experience, the following remarks can be made:

1. Power level can be controlled effectively with a closed loop integral and proportional control system, operating on output power, if adequate damping is present in the drive train.
2. The wind direction as seen at hub height is highly variable and the error band should be set quite wide (approx. $\pm 25^{\circ}$ for Mod-0) for wind turbines with positive yaw drive systems.
3. Frictional damping in yaw must be provided for the Mod-0 wind turbine to prevent large rotor and yaw drive loads from occurring during yawing operations. A damping force must also be provided when the nacelle is not yawing, otherwise the nacelle must be locked to the tower.
4. Mod-0 tests indicate that a potential exists for a free yaw downwind rotor machine. However, steps must be taken to increase the stabilizing force with rotor offset or coning, and some positive restraining force or damping in yaw may be required.

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Fig. 1.

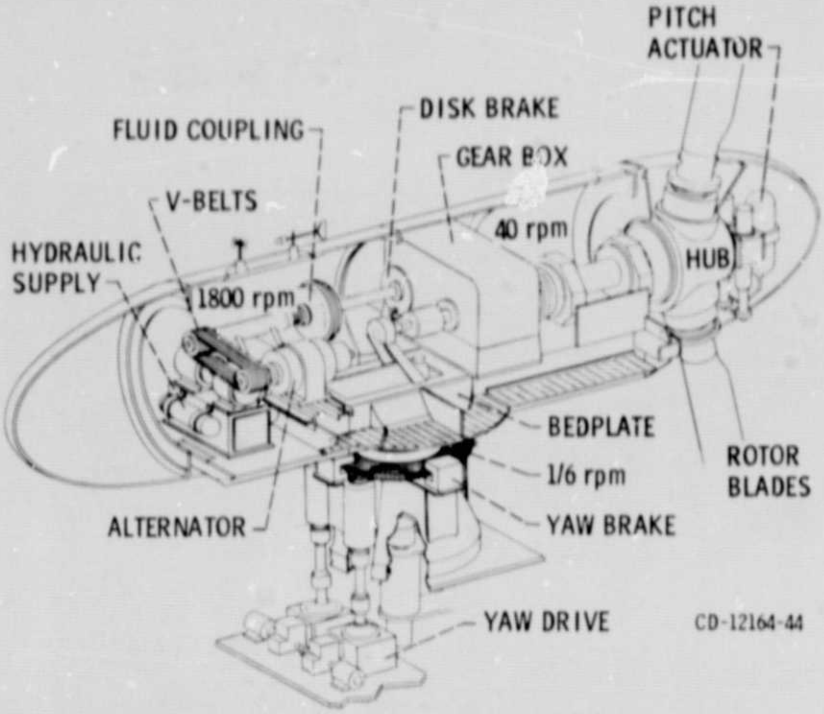

Figure 2. - Mod-O wind turbine generator schematic of nacelle interior.

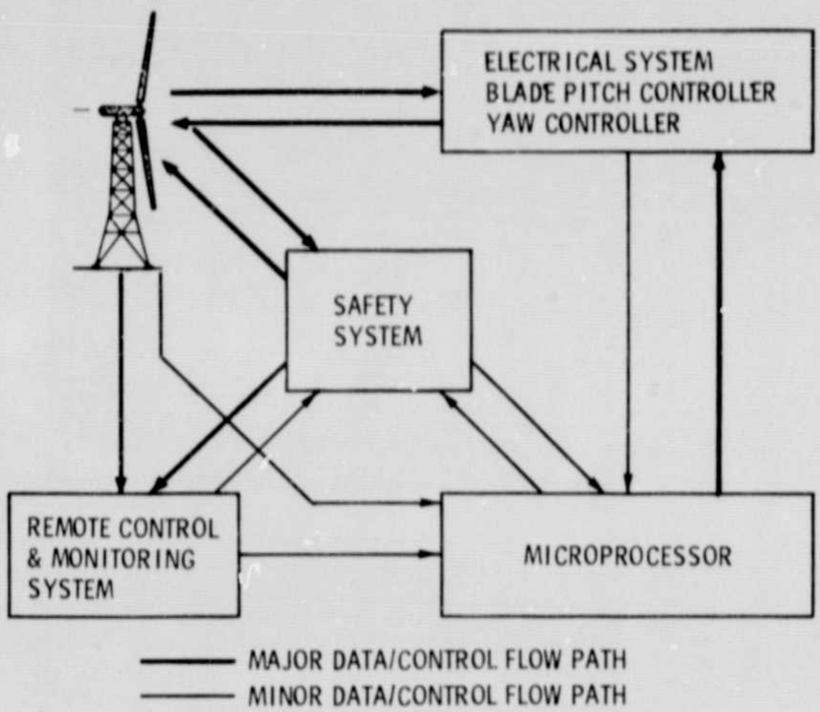

Fig. 3 - Wind turbine control system interfaces

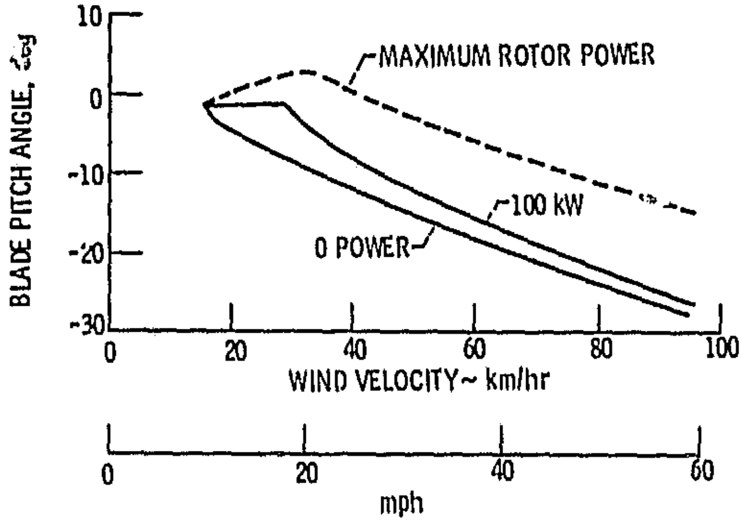

Fig. 4 - Blade pitch angle vs wind velocity for various power levels

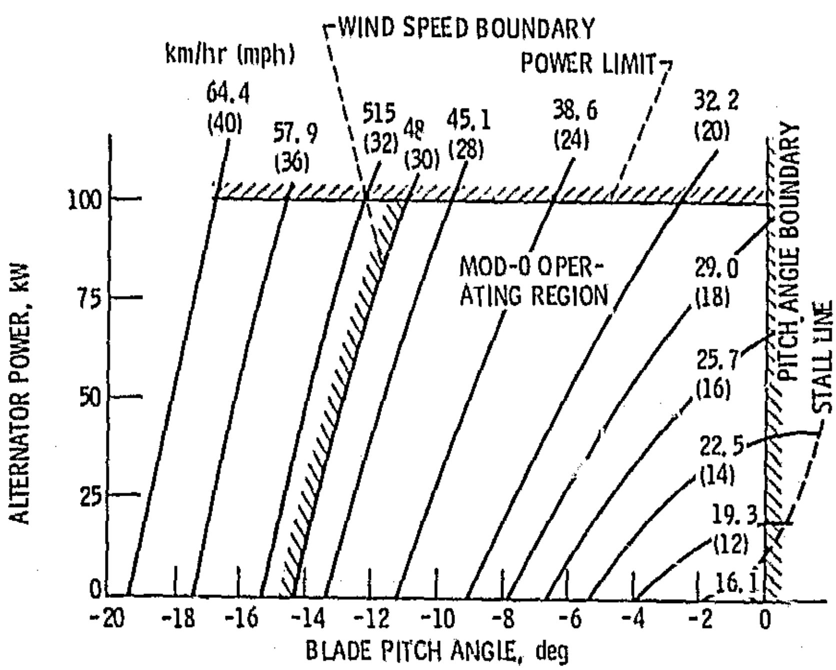

Fig. 5 - Alternator power vs blade angle for various wind speeds

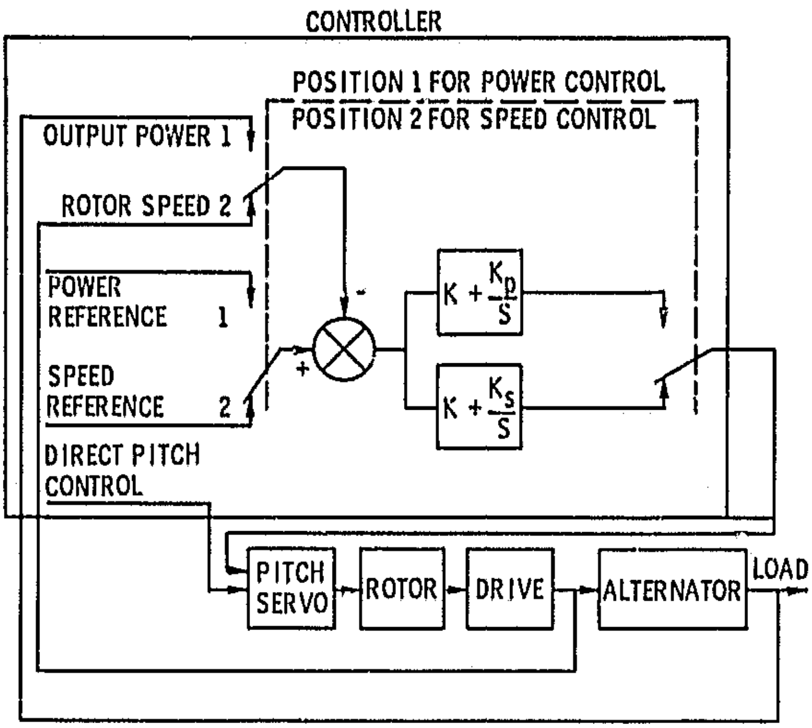

Fig. 6 - MOD-0 rotor blade pitch controller

START PITCH HYDRAULIC PUMP
RELEASE EMERGENCY FEATHER
INCREASE BLADE PITCH TO START ROTATION
SWITCH TO SPEED CONTROL
INCREASE ROTOR SPEED TO 40 rpm
TURN ON FIELD
SYNCHRONIZE
SWITCH TO POWER CONTROL
INCREASE POWER SET POINT TO 100 kW

Fig. 7 - MOD-0 100 kW wind turbine startup sequence

TRANSFER TO PITCH CONTROL
DECREASE BLADE PITCH ANGLE
DESYNCHRONIZE WHEN POWER GOES TO ZERO
TURN OFF FIELD
DECREASE PITCH TO FEATHER POSITION
OPEN EMERGENCY FEATHER VALVE
TURN OFF HYDRAULIC PUMP

Fig. 8 - MOD-0 100 kW wind turbine shutdown sequence

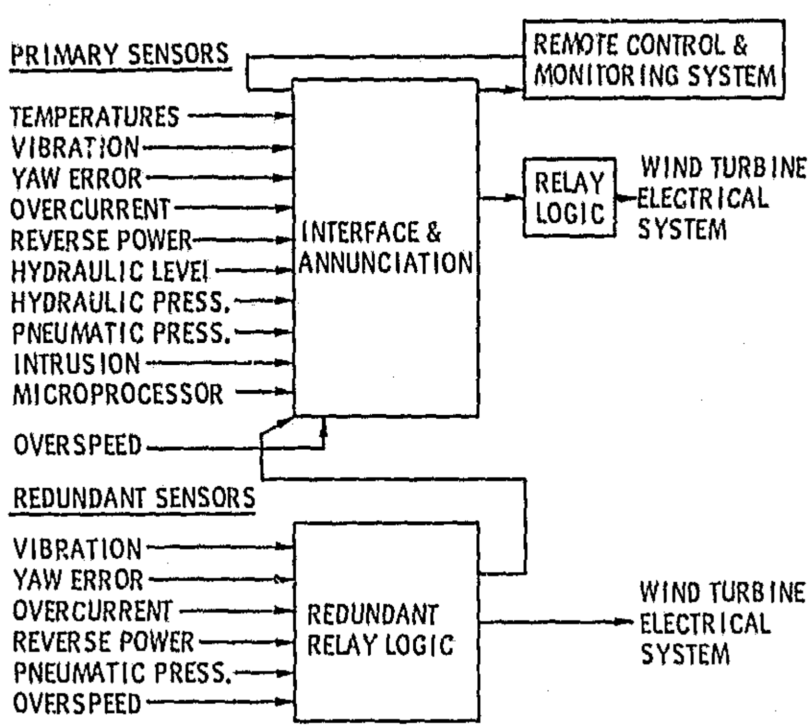

Fig. 9 - Safety system block diagram

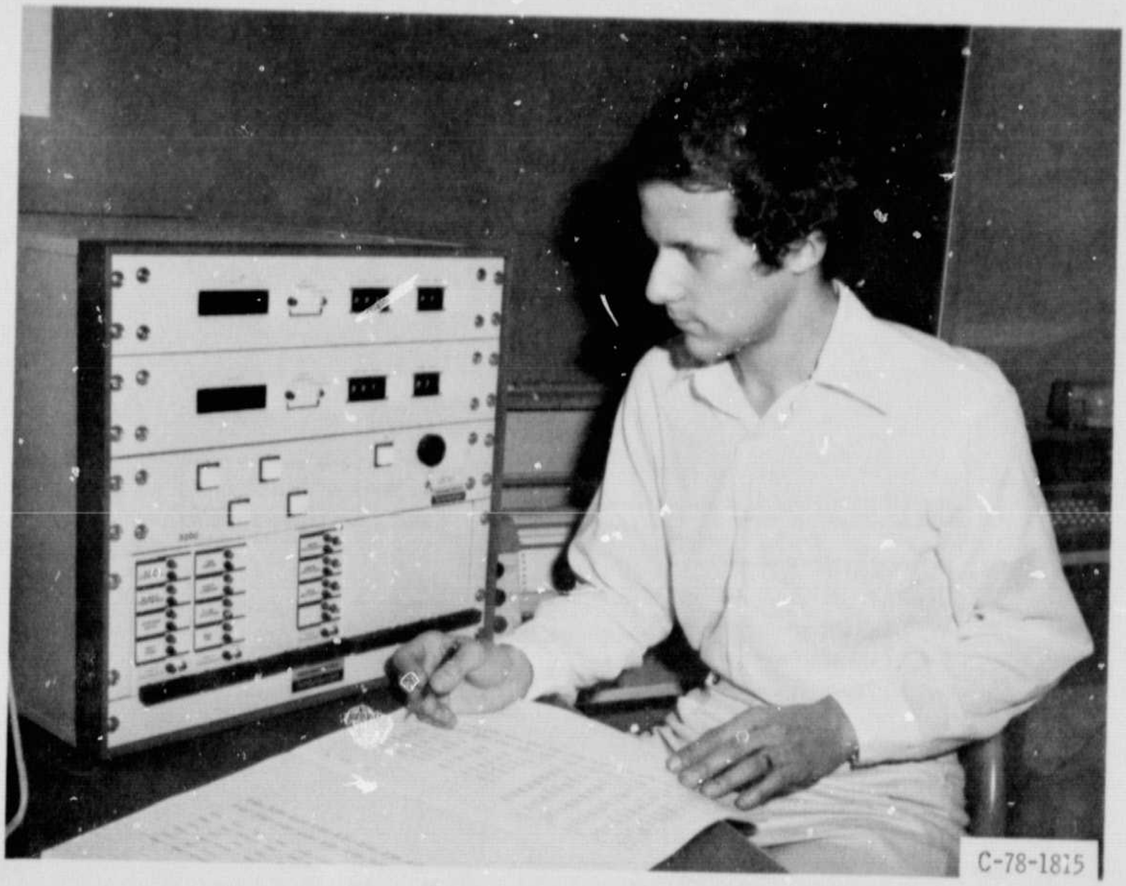

Fig. 10. - Remote control and monitoring system.

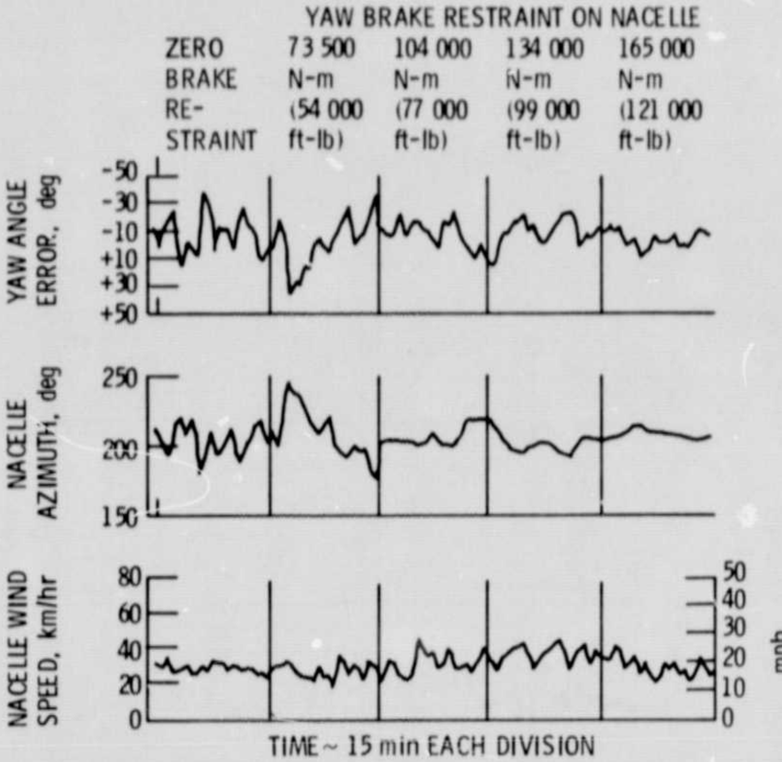

Fig. 11 - Nacelle response in free yaw

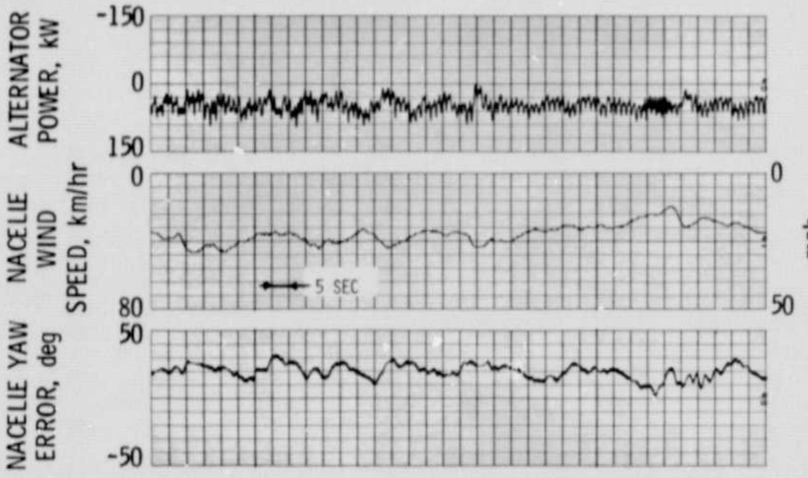

Fig. 12 - Power fluctuations with rigid high speed shaft

E-9332

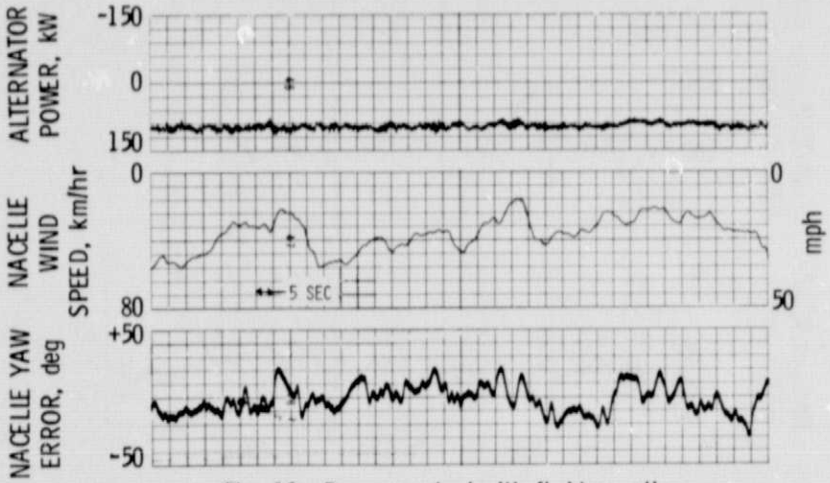

Fig. 13 - Power control with fluid coupling

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16. Abstract

The Mod-O 100 kW Experimental Wind Turbine was designed and fabricated by NASA, as part of the Federal Wind Energy Program, to assess technology requirements and engineering problems of large wind turbines. The machine became operational in October 1975 and has demonstrated successful operation in all of its design modes. During the course of its operations the machine has generated a wealth of experimental data and has served as a prototype developmental test bed for the Mod-OA operational wind turbines which are currently used on utility networks. This paper describes the mechanical and control systems as they evolved in operational tests and describes some of the experience with various systems in the downwind rotor configuration.

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