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DESCRIPTION OF THE 3MW SWT-3 WIND TURBINE AT SAN GORGONIO PASS CALIFORNIA

S. C. Rybak
The Bendix Corporation Energy, Environment and Technology Office

Abstract

The SWT-3 wind turbine, developed under an agreement between Bendix and Southern California Edison (SCE), is a microprocessor controlled three bladed variable speed upwind machine with a 3MW rating that is presently operational and undergoing system testing at SCE's Devers Substation ten miles north of Palm Springs California. The tower, a rigid triangular truss configuration, is rotated about its vertical axis to position the wind turbine into the prevailing wind. The blades rotate at variable speed in order to maintain an optimum 6:1 tip speed ratio between cut-in and rated wind velocity thereby maximizing power extraction from the wind. Rotor variable speed is implemented by the use of a hydrostatic transmission consisting of fourteen fixed displacement pumps operating in conjunction with eighteen variable displacement motors. Full blade pitch with on-off hydraulic actuation is used to maintain 3MW of output power between rated wind velocity of 40 mph and the cut-out wind velocity of 55 mph.

1.0 INTRODUCTION

In a privately funded venture, The Bendix Corporation in conjunction with Southern California Edison (SCE) Company developed and erected the SWT-3 wind turbine at SCE's Devers substation in the San Gorgonio Pass area ten miles north of Palm Springs, California. The SWT-3 has a 3MW rating and its design is based on the technology developed by Mr. Charles Schachle. The wind turbine is presently operational and is undergoing system testing to determine/verify performance characteristics. This paper describes the configuration of the SWT-3 and includes a description of major control subsystems operation as well as a brief report on the present machine status.

2.0 PHYSICAL CONFIGURATION OF THE SWT-3 WIND TURBINE

The SWT-3 wind turbine is a three bladed variable speed upwind rotor machine which employs a nacelle enclosed machinery bedplate rigidly fixed to a steel truss tower. The approximately 100 feet high tower employs a pyramid shape with a triangular base configuration approximately 75 foot on each side. The tower is rotated about its vertical axis to position the wind turbine into the prevailing wind. Rotor variable rotational speed is obtained by means of a hydrostatic transmission consisting of 14 fixed displacement pumps, 18 variable displacement motors and the associated plumbing. The fixed displacement pumps are located in the nacelle and are driven by the rotor through a step-up gear box. The variable displacement motors are located at the base of the tower in a generator enclosure and are tied to the generator through another step-up gear box. High pressure hydraulic lines run from the fixed displacement pumps to the variable displacement motors linking the two and forming the power transmission path. Three charge pumps supply fluid from a reservior to the low pressure side of the fixed displacement pumps thus completing the primary power loop. Pitch control is achieved by rotating the blades about their longitudinal axis using an on-off hydraulic actuation system. All control and housekeeping functions are microprocessor controlled, however for various critical functions whose failure could either impact system safety or result in severe wind turbine damage, hard wire loops are implemented in parallel with the microprocessor to insure that those critical operational areas are properly maintained in the event of a microprocessor failure.

A schematic diagram of the SWT-3 wind turbine is shown in Figure 1.0. The major components comprising the drive/power train is schematically shown in Figure 2.0. A top level block diagram of the microprocessor and its interaction with the wind turbine system is shown in Figure 3.0. A summary of the SWT-3 specifications and performance characteristics is given in Table 1.0. Figure 4.0 shows the estimated yearly energy gathering capability of the SWT-3 wind turbine as a function of average wind velocity at hub height. Figure 5.0 shows the estimated power output as a function of average wind velocity at hub height. A more detailed description of the SWT-3 design and control system operation is given in the paragraphs that follow.

3.0 OVERALL WIND TURBINE SYSTEM DESCRIPTION

The SWT-3 wind turbine was designed to produce 3MW of electrical power output in a prevailing wind of 40 mph at a rotor rotational speed of 41 rpm. The wind turbine design allows for operation in wind speeds between 8 and 55 mph once the wind turbine has been turned on. However for the wind turbine to be activated the prevailing wind must be between 12 and 55 mph. For winds in excess of 55 mph the wind turbine will not turn on, or if operating will automatically shut itself off.

Three major subsystems control the SWT-3 wind turbine. They are the rotor speed control subsystem, the blade pitch control subsystem, and the tower yaw control subsystem. A description of each of these control subsystems is given in what follows.

3.1 Rotor Speed Control Subsystem

In order to extract the maximum amount of energy from the wind for wind speeds between 8 and 40 mph a 6 to 1 speed ratio must be maintained between the blade (rotor) tip speed and the wind velocity i.e., the blade tips must have a linear velocity which is six times that of the wind velocity perpendicular to the disc swept by the rotor. In order to maintain this speed ratio for wind speeds varying between 8 and 40 mph the rotor rpm needs to vary accordingly. For the geometry

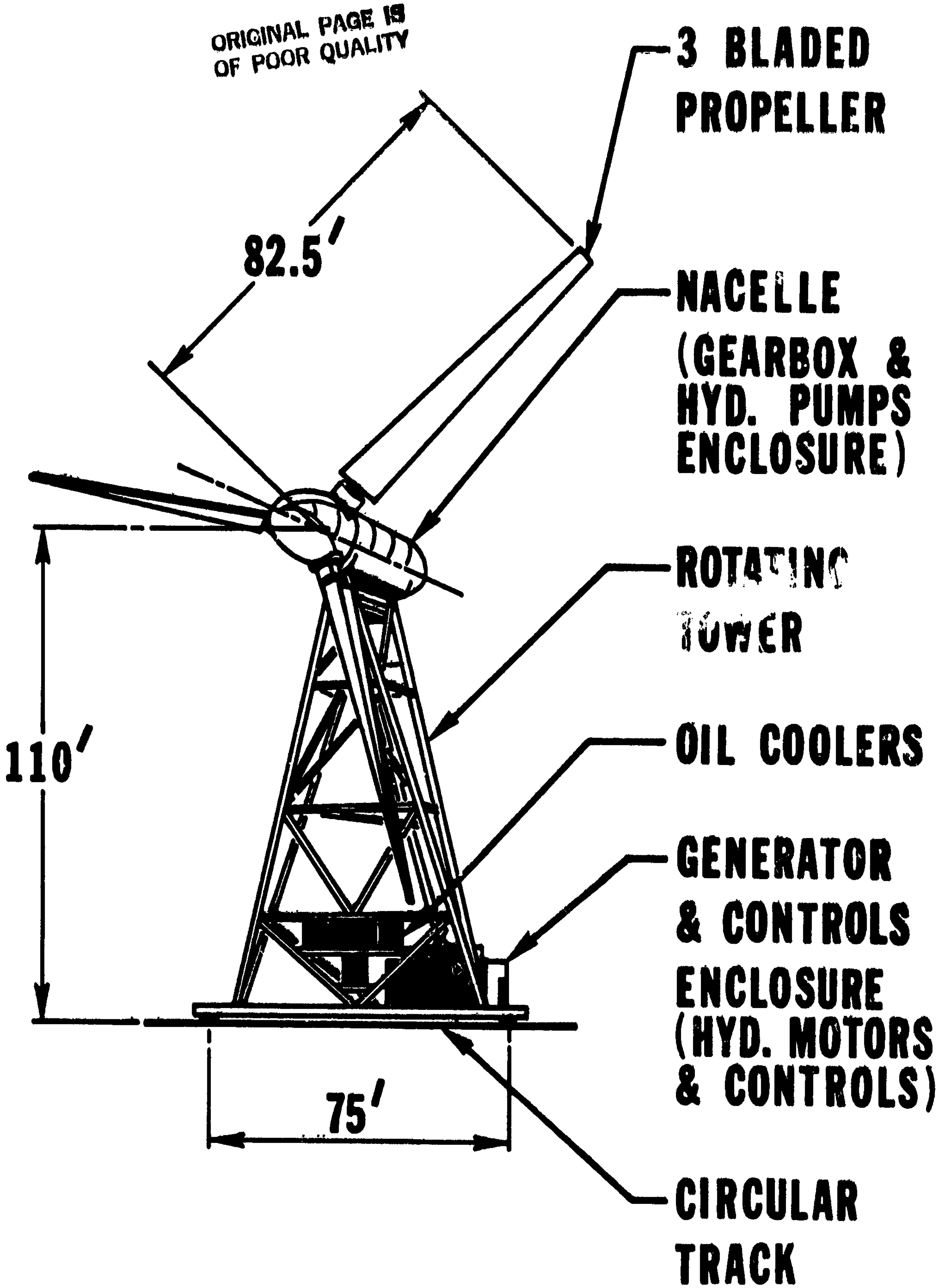

FIGURE 1.0 SCHEMATIC DIAGRAM OF SWT-3 WIND TURBINE

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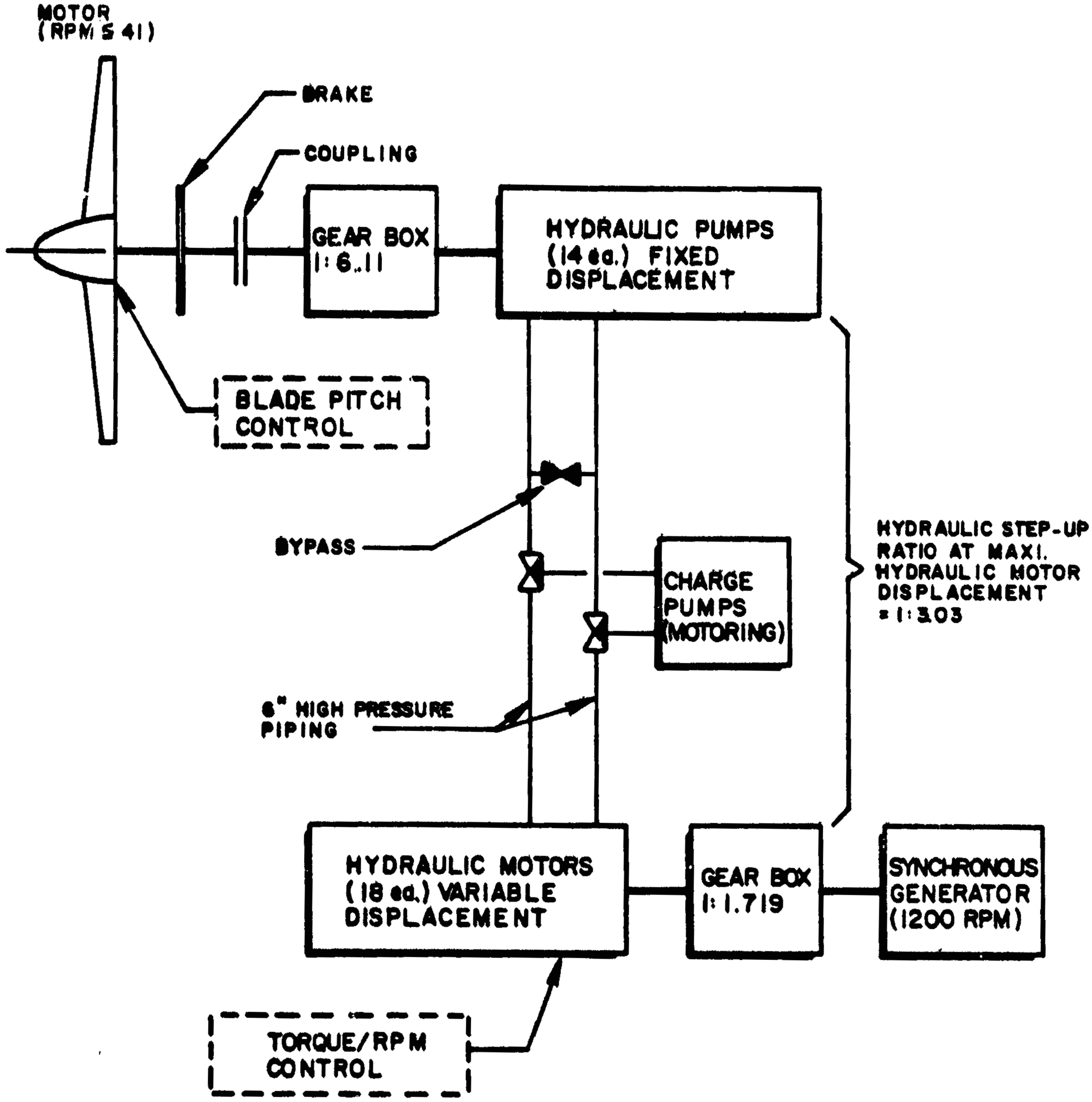

FIGURE 2.0 SCHEMATIC DIAGRAM OF SWT-3 DRIVE/POWER TRAIN

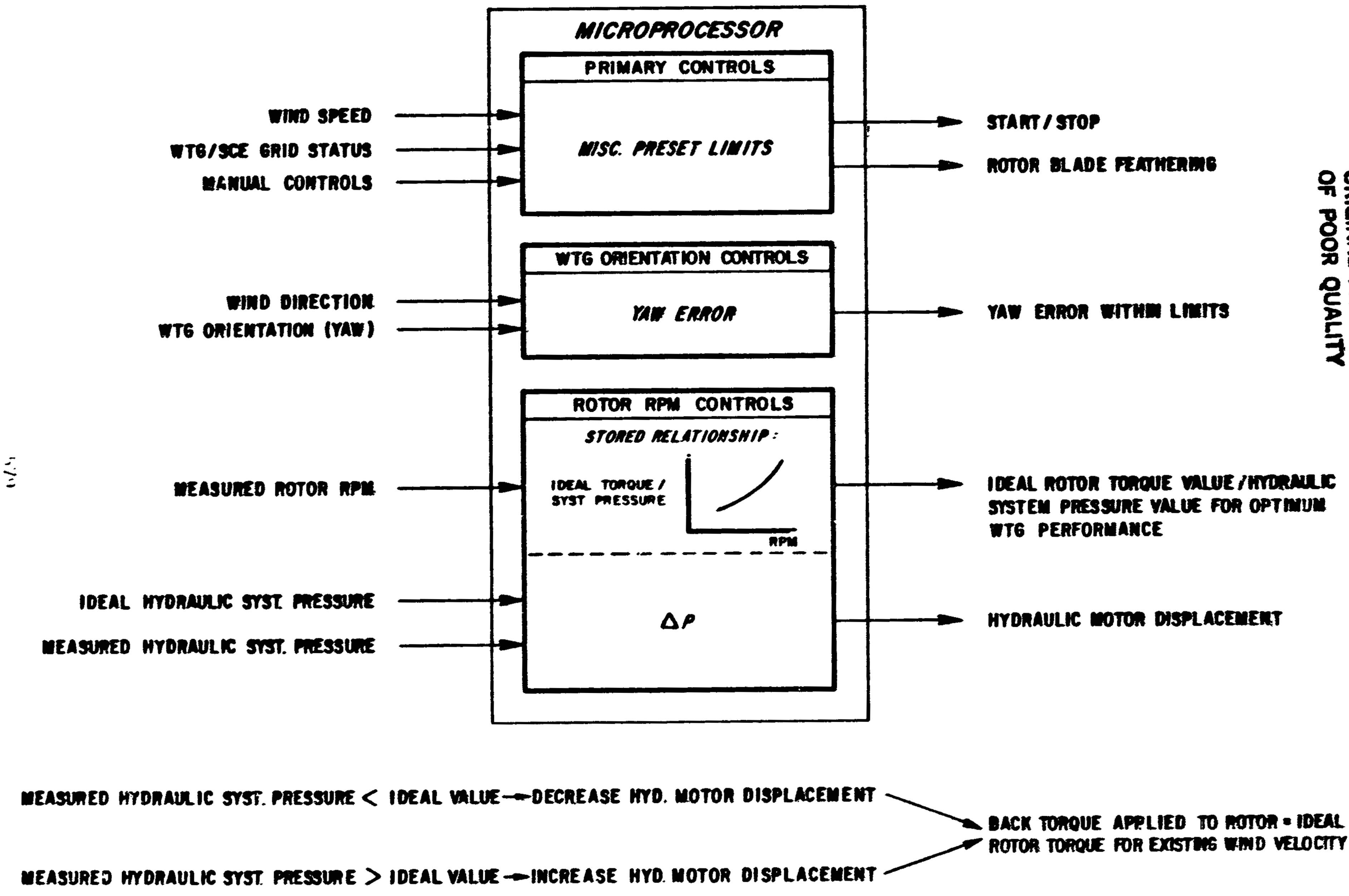

FIGURE 3.0 MICROPROCESSOR BLOCK DIAGRAM

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TABLE 1.0 BENDIX SWT-3 WIND TURBINE GENERATOR CHARACTERISTICS

RATED POWER	3,000 KW
ROTOR DIAMETER	169 FT
ROTOR TYPE	3-BLADE HORIZONTAL AXIS
ROTOR AIRFOIL	SCHACHLE
ROTOR ORIENTATION	UPWIND
ROTOR TIP SPEED	VARIABLE - 6 TIMES THE WIND VELOCITY
RATED WIND VELOCITY	40 MPH
ROTOR ROTATIONAL SPEED AT RATED POWER	41 RPM
CUT-IN WIND VELOCITY	12 MPH
CUT-OUT WIND VELOCITY (HIGH END)	55 MPH
CUT-OUT WIND VELOCITY (LOW END)	8 MPH
GENERATOR TYPE	SYNCHRONOUS
GENERATOR ROTATIONAL SPEED	1,200 RPM
GENERATOR VOLTAGE	4,160 VOLTS
POWER FACTOR	1.0 AT FULL LOAD
HARMONIC CONTENT	2%
DEVIATION FACTOR	3%
GENERATOR EFFICIENCY	96.5% AT FULL LOAD
GENERATOR ROTATIONAL SPEED	1,200 RPM
POWER TRANSMISSION SYSTEM	HYDROSTATIC (14 FIXED DISPLACEMENT PUMPS WITH 18 VARIABLE DISPLACEMENT MOTORS)
PUMP DISPLACEMENT	150.6 IN^3/REV PER PUMP
MOTOR DISPLACEMENT	38.63 IN^3/REV PER MOTOR MAXIMUM DISP. 11.4 IN^3/REV PER MOTOR MINIMUM DISP.
UPPER GEAR BOX	HELICAL SPUR GEAR 1:6.11 STEP-UP
LOWER GEAR BOX	HELICAL SPUR GEAR 1:1.719 STEP-UP
PITCH CONTROL	HYDRAULIC ON-OFF ACTUATION
TOWER	TRIPOD CONFIGURATION, RIGID TRUSS CONSTRUCTION, ROTATING FOR YAW CONTROL
TOWER ROTATION SYSTEM	HYDRAULIC ON-OFF ACTUATION
HUB HEIGHT	110 FT
FOUNDATION	CIRCULAR - 78.5 FT DIAMETER
SYSTEM POWER COEFFICIENT	0.38 - FROM CUT-IN TO RATED POWER
AVAILABILITY FACTOR	0.95
TOWER YAW RATE	36 DEG/MIN
BLADE PITCHING RATE	1^{o}DEG/SEC NORMAL OPERATION 2 DEG/SEC EMERGENCY OPERATION

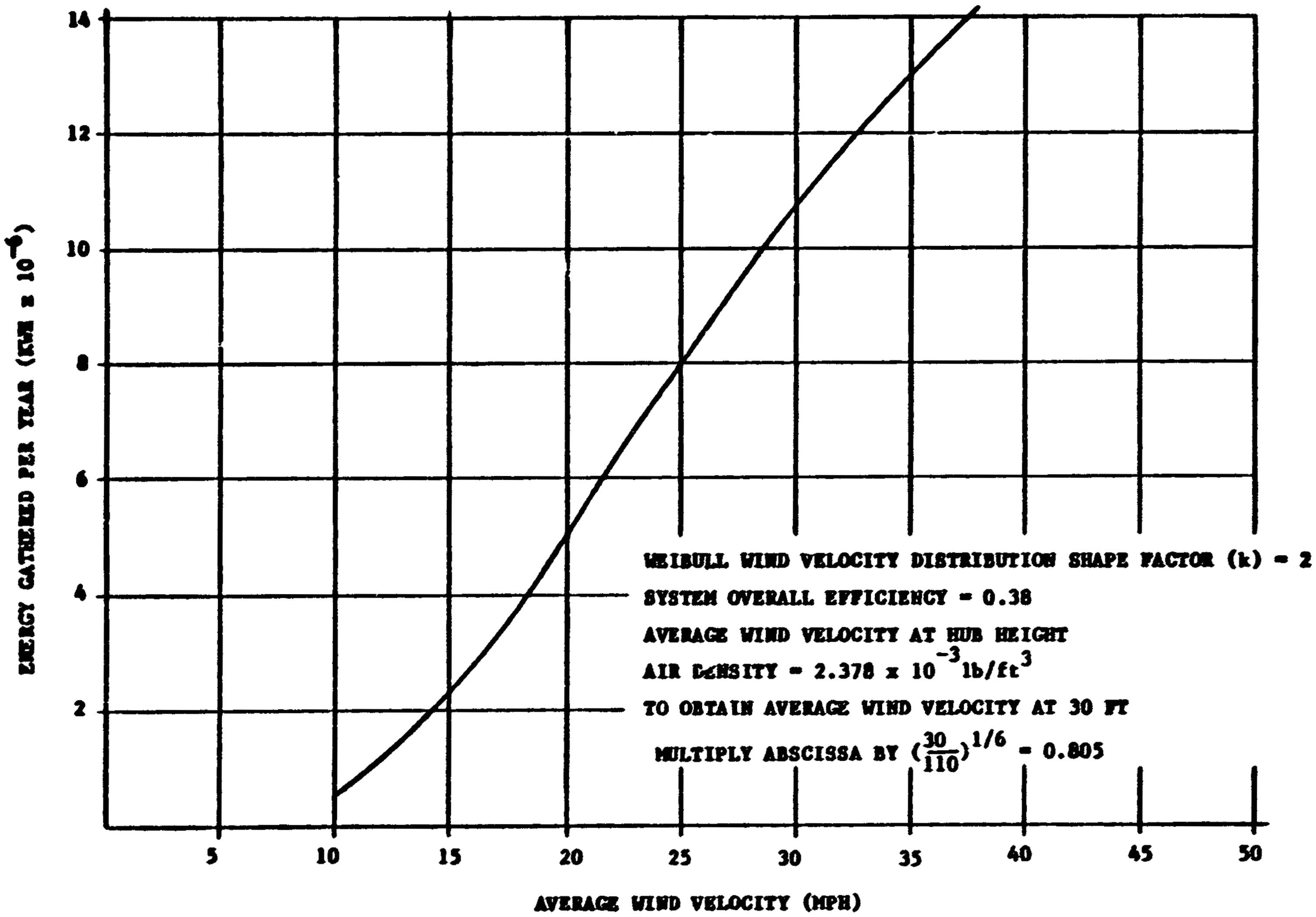

FIGURE 4.0 ENERGY GATHERED PER YEAR AS A FUNCTION OF AVERAGE WIND VELOCITY AT HUB HEIGHT (ESTIMATED)

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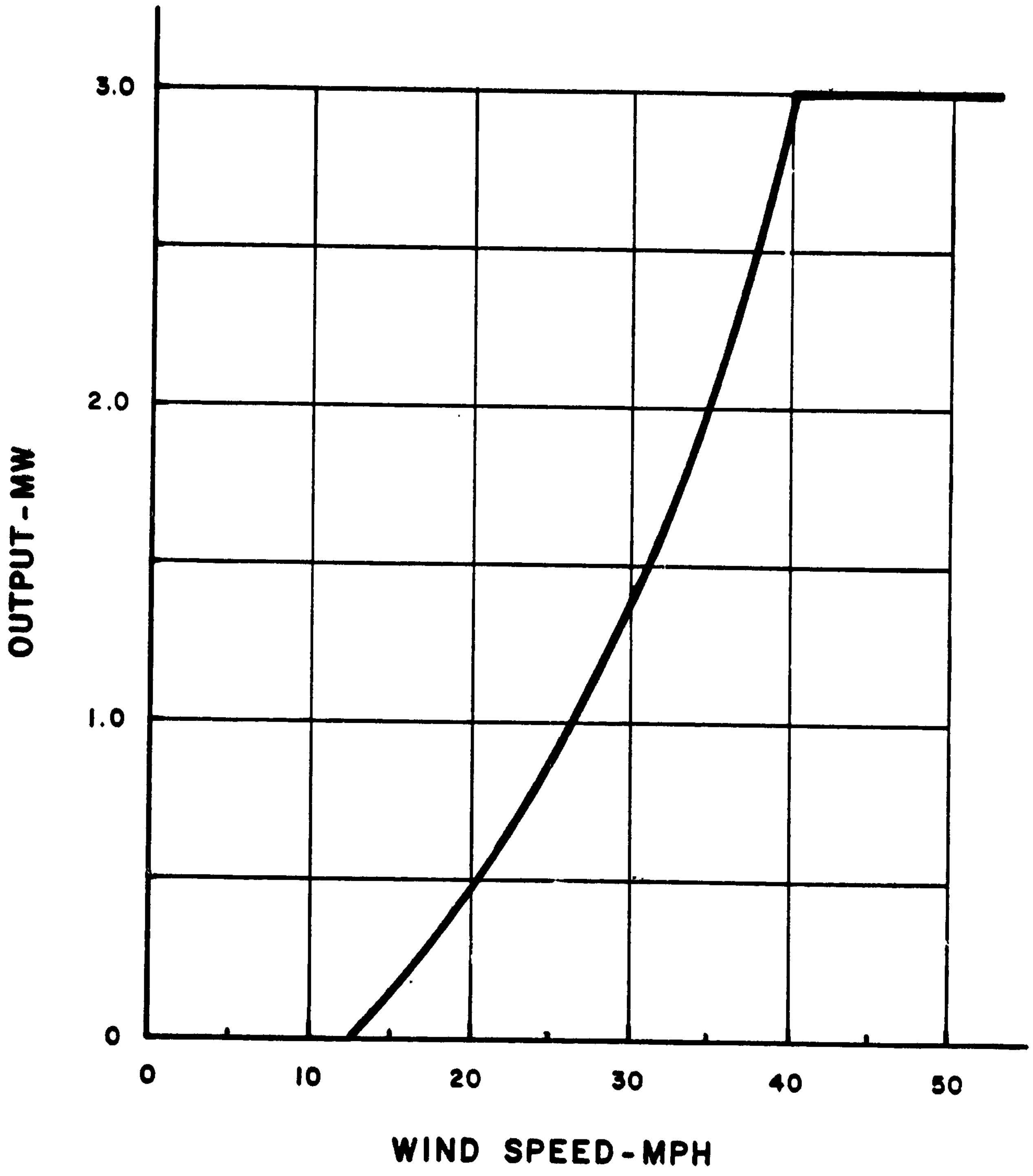


FIGURE 5.0 ESTIMATED OUTPUT POWER AS A FUNCTION OF AVERAGE WIND VELOCITY AT HUB HEIGHT

A block diagram of the rotor power/speed control loop intended to command the variable displacement motor is shown in Figure 6.0. The rotor rpm, as indicated by the tachometer mounted on the rotor shaft, is used to determine, from the microprocessor stored look-up table, what the system pressure should be for the particular rotor rpm. That system pressure in turn becomes the command pressure. The actual system pressure is measured by a pressure transducer which is passed through a low pass filter to avoid reacting to "high" frequency pressure spikes and to insure required loop stability and response characteristics. The system pressure is differenced with the command pressure and a pressure error determined. This error data is then passed through a variable speed deadband whose output commands the on-off solenoid valve thereby varying the motor displacements. The variable deadband methodology is employed to avoid/diminish speed control loop limit cycling which would in turn stress system components.

3.2 Rotor Pitch Control Subsystem

When the wind speed exceeds 40 mph but is below 55 mph the wind turbine will generate rated power (i.e. 3 MW) while the rotor speed is maintained at approximately 40 rpm. This is accomplished by pitching the rotor blades on the basis of system pressure limits (4,200 psi), rotor rpm limits (40 rpm), and generator speed limits (1,200 rpm). Pitching the rotor has the effect of maintaining the applied wind torque constant in wind regimes between 40 and 55 mph thereby maintaining rated power output. Actually, due to the on-off implementation of the pitch control, the blade pitch angle, and hence the power output, will limit cycle. The amplitude of the limit cycles are reduced to acceptable levels by the inclusion of appropriate loop compensation. A block diagram of the pitch control loop is shown in Figure 7.0.

When the pitch control loop is activated the system pressure will vary due to the blade pitching action. The rotor power/speed control loop uses this parameter in order to adjust the variable motor displacements to maintain optimum system pressure and rotor rpm. However, the curve relating system pressure to rotor rpm assumes that the rotor blades are at their optimum pitch. Therefore if the speed control loop is allowed to operate when the rotor blades are pitching, erroneous information will be fed into the power/speed control loop. Those signals will in turn erroneously and needlessly change motor displacement. In order to preclude such needless motor displacement changes the .power/speed control loop is disabled when the blades are commanded to pitch.

3.3 Yaw Control Subsystem

The yaw control loop rotates the wind turbine into the wind so that the wind direction is within an acceptable angular error with respect to the perpendicular to the plane defined by the rotor blades. The control loop is implemented by having a tower mounted wind vane which measures the wind direction with respect to the tower. The wind vane signal is passed through a low pass filter in order to avoid responding to "short" term wind direction variations which otherwise would unduly stress the yaw control system actuation components.

Since the tower can only rotate 330° the command to the yaw actuator must take into consideration the angular position of the tower to avoid rotating it through its stops. This is accomplished by having an angular transducer which measures the tower angular position. The tower angular transducer measurement is added of the SWT-3 wind turbine (i.e. blade tip to center of rotation of approximately 84.5 ft.) the rotor rpm should approximately equal the velocity of the wind given in mph to maintain the 6:1 speed ratio. However, the generator, to which the rotor is coupled, is a synchronous machine running at a constant 1,200 rpm. Therefore, if the rotor speed is to vary, the rotor must be coupled to the synchronous generator through a variable speed (i.e.gear ratio) transmission.

The variable speed transmission employed utilizes hydrostatic principles which are implemented by fourteen fixed displacement pumps operating in conjunction with eighteen variable displacement motors. As the motor displacements are varied the effective gear ratio between the rotor and the synchronous generator varies accordingly, allowing the rotor to rotate at varying rates while maintaining a constant rotation rate at the synchronous generator.

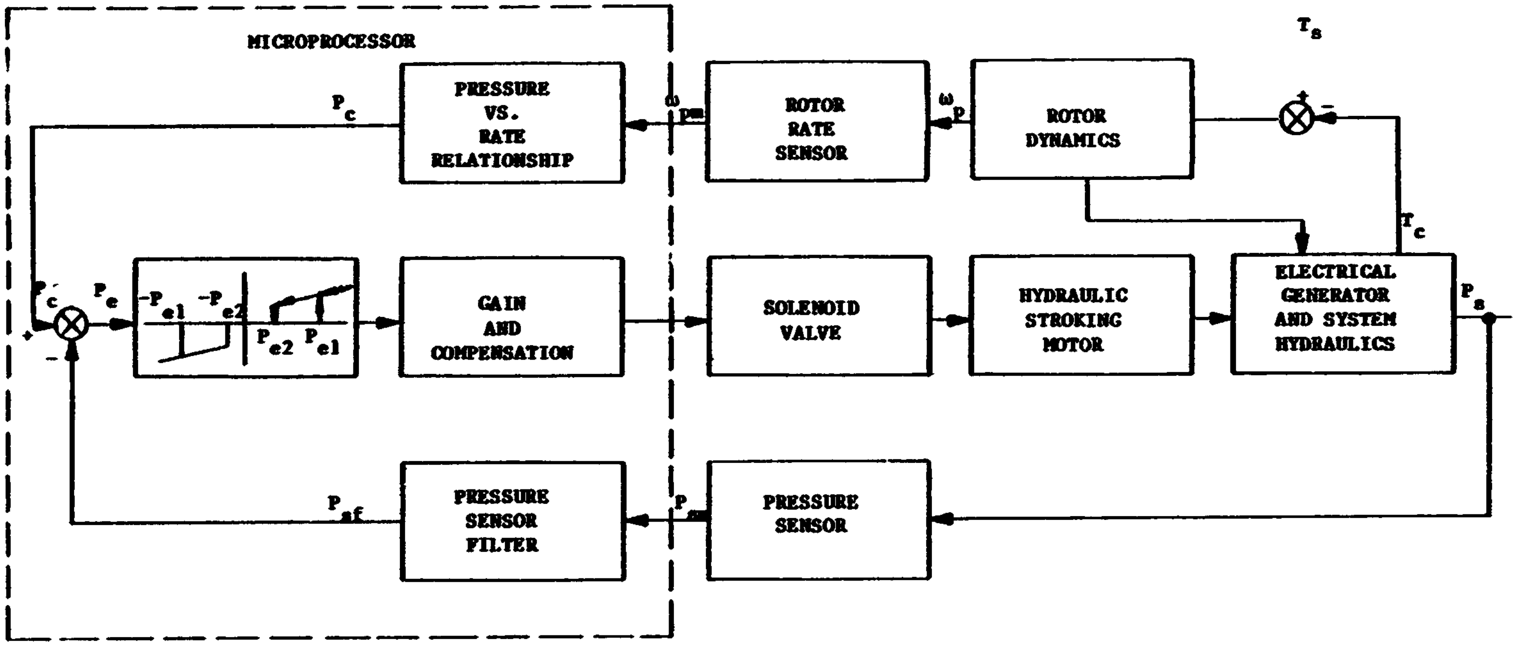
To maintain the rotor at a particular desired rpm the summation of the torques applied to the rotor must equal zero. The torques applied to the rotor consist of those applied by the wind (T_w), the back torque applied by the synchronous generator through the hydraulics reflected to the rotor shaft (T_g), and the torque applied to the rotor due to losses in the system (T_l). Therefore the following relationship must apply for the rotor to remain in equilibrium and maintain constant speed.

$$T_w - T_g - T_l = 0 \qquad (1)$$

Assuming that the system losses are small or $T_l \ll 1$ then the following applies

$$T_w \approx T_g \qquad (2)$$

Consequently it is clear that for the rotor to maintain constant rpm, the torque applied by the wind on the rotor must be approximately counterbalanced by the torque applied to the rotor by the generator through the system hydraulics. This torque is directly proportional to the pressure in the main hydraulic lines under steady state conditions. When the variable motor displacements are set to a value corresponding to a gear ratio N_g, which in turn corresponds to a particular rotor speed for a synchronous generator speed of 1,200 rpm, the pressure in the hydraulic lines will increase to a point where the back torque applied to the rotor approximately equals the torque applied by the wind to the rotor thereby keeping it in equilibrium and maintaining its speed constant at a value corresponding to the hydraulic motor displacement setting. If the relationship between the applied wind torque on the rotor as a function of rotor rpm is known, assuming the optimum speed ratio of 6:1 is maintained, measurement of the generator applied torque compared to the value of torque one should have for a particular rotor rpm will establish whether this value is proper for the measured rotor rpm. Depending whether the generator applied torque is greater or less than the optimum value for the measured rotor rpm the hydraulic motor displacement can be increased or decreased respectively until the optimum pressure and rotor rpm occur simultaneously. Since the applied generator torque acting through the system hydraulics is in the steady state directly proportional to system hydraulic pressure, system pressure could be measured in lieu of measuring the applied torque directly. Measurement of system pressure is considerably easier than measurement of the torque applied by the generator consequently system pressure measurement is used to implement the rotor speed control loop.



T_a = TORQUE APPLIED TO PROPELLER BY WIND

T_c = TORQUE APPLIED TO PROPELLER BY HYDRAULICS

P_c = COMMAND PRESSURE

P_s = ACTUAL SYSTEM PRESSURE

P_{sm} = MEASURED SYSTEM PRESSURE

P_{sf} = FILTERED SYSTEM PRESSURE

ω_p = ROTOR RATE

ω_{pm} =MEASURED ROTOR RATE

P_{e1} = ACTUATION PRESSURE ERROR LEVEL

P_{e2} = SHUTOFF PRESSURE ERROR LEVEL

P_e = PRESSURE ERROR

FIGURE 6.0 BLOCK DIAGRAM OF POWER/SPEED CONTROL LOOP

P_{co} = COMMAND PRESSURE

P_s = SYSTEM PRESSURE

θ_{pc} = PITCH ANGLE COMMAND

θ_{plm} = MEASURED PITCH ANGLE

T_a = TORQUE APPLIED TO THE ROTOR BY WIND

T_c = TORQUE APPLIED TO THE ROTOR BY HYDRAULICS

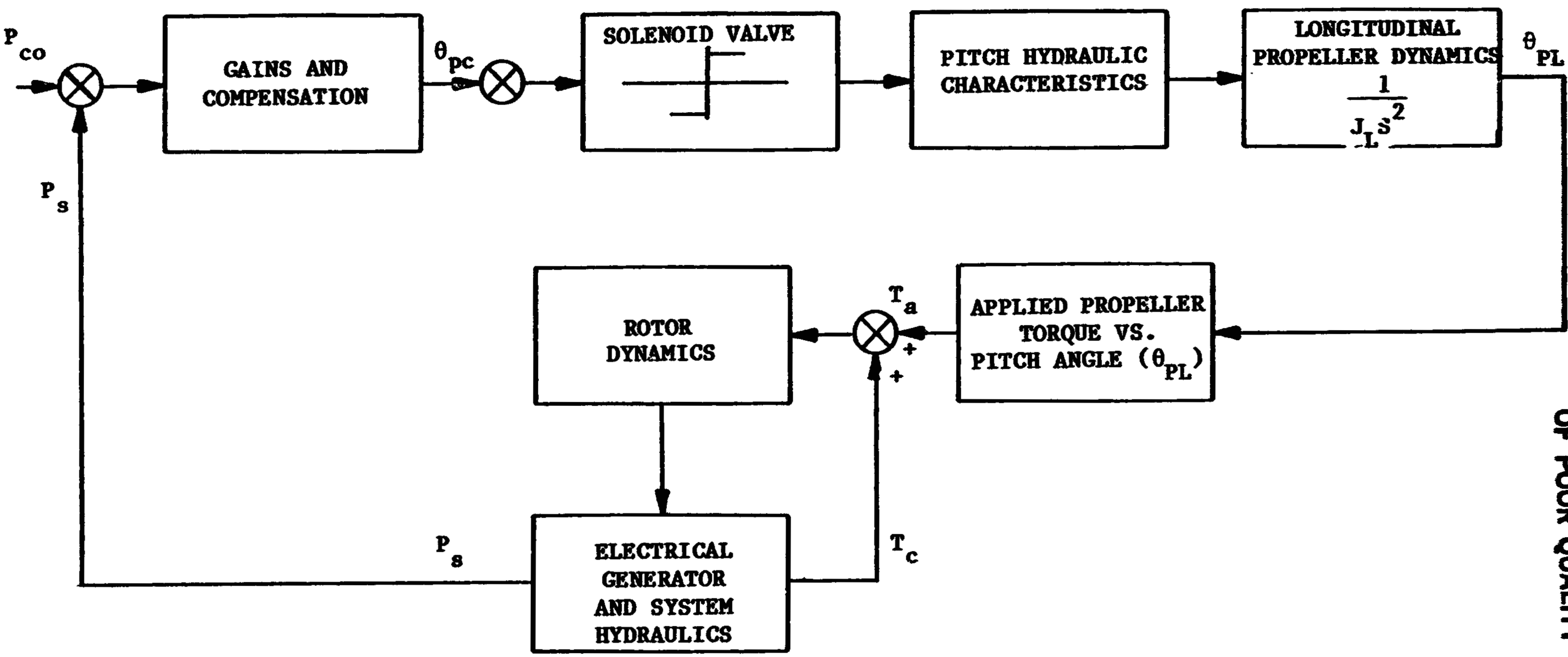


FIGURE 7.0 BLADE PITCH CONTROL LOOP

to the wind vane measurement (which measures the wind direction relative to the tower) to obtain the tower command angle. The tower command angle is examined to determine if it is larger than 360°. (This condition can happen since both the tower angular transducer and the anemometer read positive angles between 0° and 360° when they rotate counterclockwise). If the tower command angle exceeds 360° then 360° is subtracted from the command and the new tower command angle is obtained. If the tower command angle does not exceed 360° then it becomes the new tower command angle. The tower command angle thus generated is then screened to determine if it is in the allowable region for tower angular position. If the new tower angular command is in the region between 330° and 360° it is then determined if the new tower command angle is less or greater than 345° (i.e. midpoint of the region the tower cannot rotate through). If the new tower command angle is between 330° and 345° the tower will be commanded to rotate to 330°. If the new tower command angle is between 345° and 360° the tower will be commanded to zero degrees. However, should it be necessary to command the wind turbine to initially rotate away from the prevailing wind direction in order to avoid the tower stops, it may be necessary to take the wind turbine off-line to avoid stressing the blades and causing the generator to excessively motor. The necessity of taking the wind turbine off-line under those conditions is still under evaluation, however the control algorithms required can easily be accomodated by the microprocessor.

A block diagram of yaw control loop is shown in Figure 8.0. As seen from the figure a variable deadband implementation is used to avoid chasing the wind thereby eliminating excessive yaw actuations which would otherwise result in the presence of relatively small wind variations.

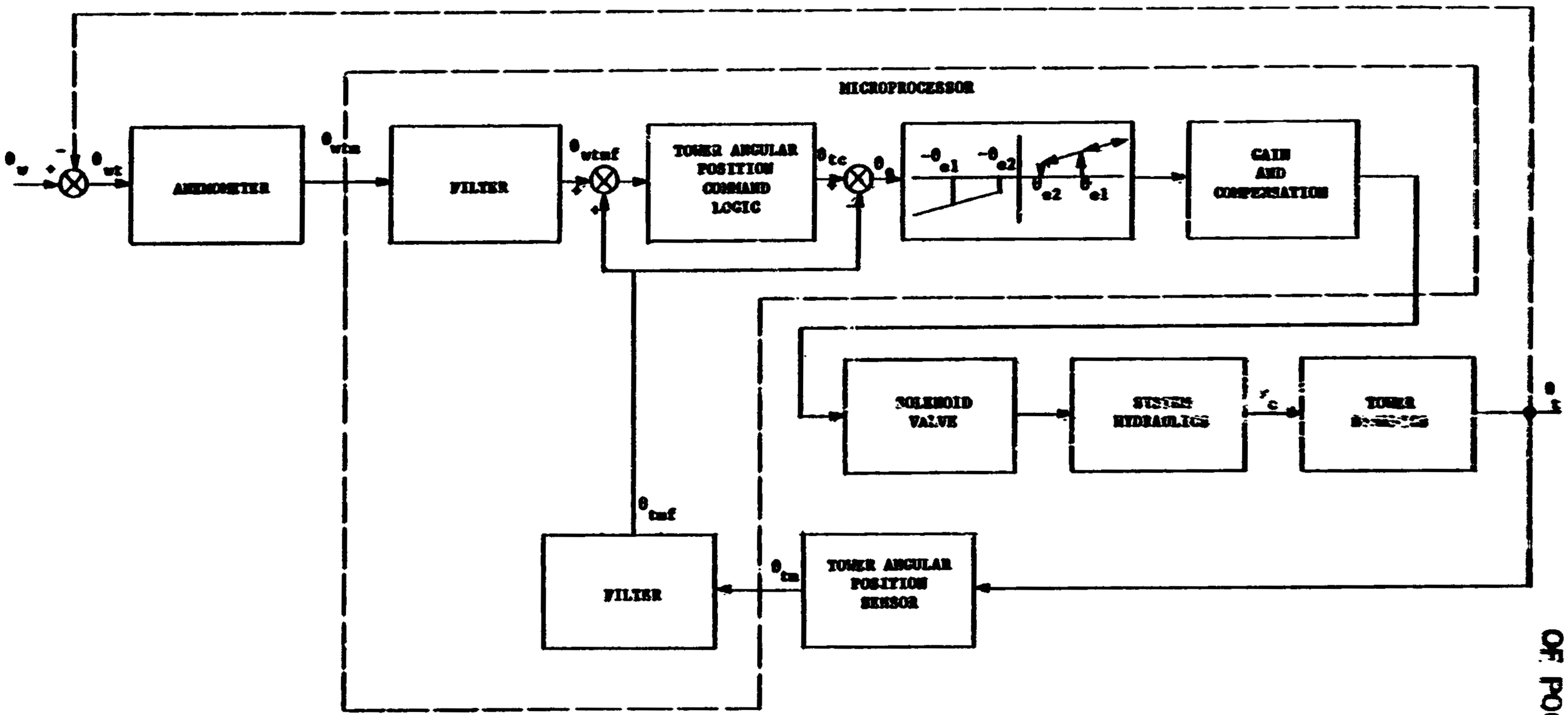
4.0 SWT-3 STATUS

The SWT-3 wind turbine was officially commissioned on December 16, 1980. Since that time the wind turbine has been under going system testing in order to determine and verify system stability and performance characteristics. Early in the testing program it became apparent that modifications would be required in the grid synchronization procedure in order to reliably put the wind turbine on-line. The modifications included the addition of a synchroscope and alterations to the control logic for the variable displacement motors. Once these modifications were implemented the wind turbine synchronization to the grid is reliable and operates smoothly.

The wind turbine operational envelope has been steadily expanded as system test and checkout proceeds. At present the wind turbine has generated approximately 1.1 MW of power at a rotor rotational speed of 21 rpm.

ACKNOWLEDGEMENT

The author expresses his graditude to the Southern California Edison Company for their overall interest and assistance in preparation of the above paper. In particular the author would like to acknowledge that the schematic diagrams of the wind turbine (Figure 1.0) and the drive/power train (Figure 2.0), the microprocessor block diagram (Figure 3.0) and the estimated wind turbine output power as a function of wind speed (Figure 5.0) used in the paper to enhance the description of the SWT-3, was furnished by Mr. Michel Wehrey of the Southern California Edison Company.



θ_w = WIND DIRECTION

θ_{wt} = WIND DIRECTION WITH RESPECT TO TOWER

θ_{wtm} = MEASURED WIND DIRECTION WITH RESPECT TO TOWER

θ_{tc} = TOWER ANGULAR POSITION COMMAND

θ_e = TOWER ANGULAR ERROR

θ_t = TOWER ANGULAR POSITION

θ_{tm} = MEASURED TOWER ANGULAR POSITION

θ_{e1} = TOWER ACTIVATION ERROR LEVEL

θ_{e2} = TOWER DEACTIVATION ERROR LEVEL

T_c = TOWER CONTROL TORQUE

FIGURE 8.0 YAW CONTROL LOOP