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MULTIPLE AND VARIABLE SPEED ELECTRICAL GENERATOR SYSTEMS FOR LARGE WIND TURBINES

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ABSTRACT

A cost-effective method to achieve increased wind turbine generator energy conversion and other operational benefits through variable speed operation is presented. Earlier studies of multiple and variable speed generators in wind turbines have been extended for evaluation in the context of a specific large sized conceptual design. System design and simulation have defined the costs and performance benefits which can be expected from both two speed and variable speed configurations.

BACKGROUND

A previous paper by the authors(1) reported an examination of the costs and energy capture performance expected for a spectrum of single, two, three, and variable speed generator designs in wind turbine applications. That study concluded that the two speed Westinghouse Pole Amplitude Modulated (PAM) generator could provide a cost effective 13 percent improvement in energy capture and that more expensive variable speed concepts require cost justification beyond their 20 percent energy capture improvement.

The key to the sensitivity of annual energy capture to speed of operation is the variation of the rotor performance coefficient C_p with the ratio of blade tip speed to wind speed shown in Figure 1. In single, constant speed wind turbine rotor operation, the tip-speed ratio varies inversely with the wind speed, and the efficiency of rotor energy capture of the wind, C_p, reaches its maximum value at just one point. As shown in Figure 2, continuously variable rotor speed operation between 12.7 and 19 rpm would allow C_p to be maximized between 7 and 10.5 m/s while two speed operation suffers a 12 percent degradation of 9 m/s.

TWO SPEED SYSTEM DESIGN

The specifications for comparison of generating systems evaluated are shown in Table 1.

The PAM generator is an asynchronous (induction) alternating current machine with a single stator winding and speeds available in a variety of ratios between one and two. It differs from conventional single speed AC induction generators only in winding design since construction details are identical. PAM is a method of obtaining

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AERODYNAMIC ROTOR EFFICIENCY CURVE (Cp)

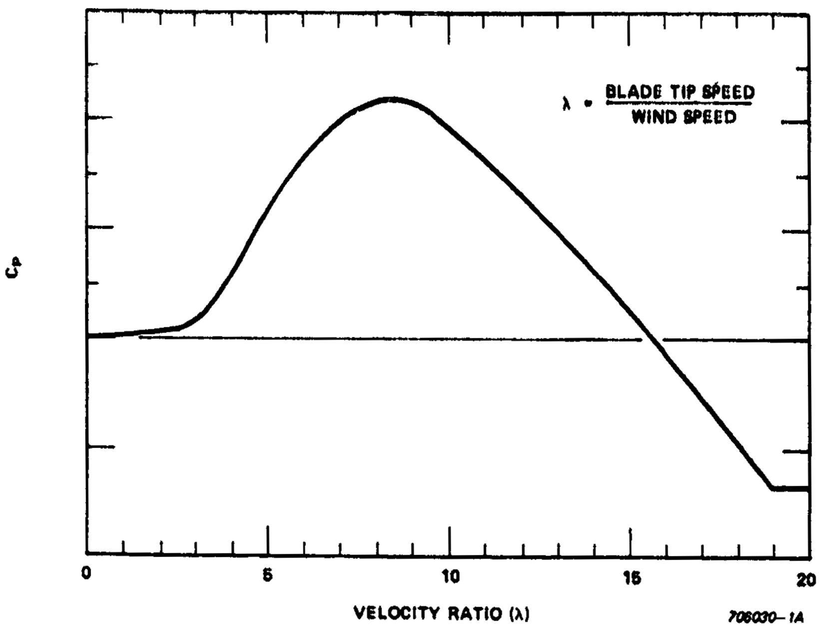

Figure 1

BLADE EFFICIENCY AS A FUNCTION OF WIND SPEED AND ROTOR SPEED

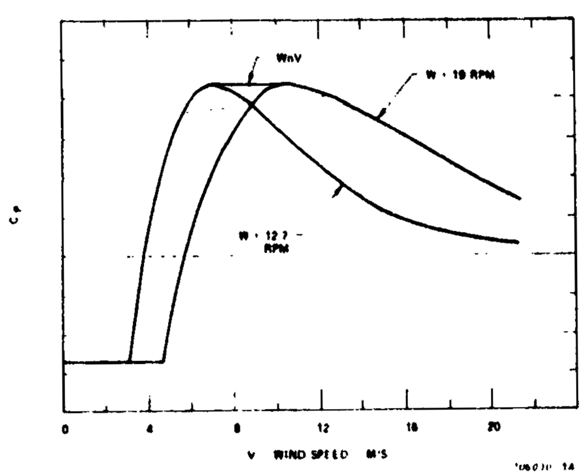

Figure 2

PAM SCHEMATIC DIAGRAM

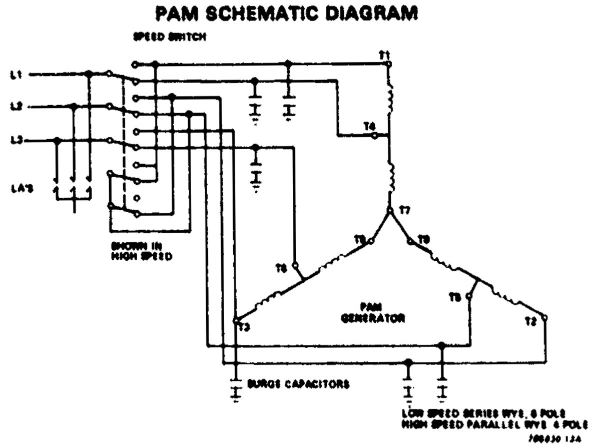

Figure 3

two speeds from a single winding, three phase squirrel cage induction machine. It is accomplished by simply changing the connections to the six main leads of the stator. The internal motor coil connections are not changed, but one half of the coils are reversed in polarity (modulated) and the number of parallels in the motor winding are changed as the main leads are reconnected.

The baseline PAM generator selected for comparison is a 6,000hp, 1800/1200 rpm machine which requires a five pole double throw speed switch to reconfigure the machine windings to achieve four pole and six pole operation. Since the PAM is an induction generator, a bank of capacitors is provided in the design to accommodate the magnetizing current of the machine and provide for power factor correction. Switchgear is located at the interface with the utility to isolate the machine from the network during periods of shutdown and during speed changing operations.

Two sets of winding configurations were evaluated for the baseline PAM. The machine can be configured with the windings for low speed (6 pole) operation series delta and for high speed (4 pole) operation parallel wye. Figure 3 shows the windings for low speed (6 pole) operation series wye connected and for high speed (4 pole) operation parallel wye connected along with the speed switch, surge capacitors, and lightning arresters. As a result of its higher equivalent impedance, use of the series wye configuration for the motoring mode results in minimum inrush current and peak torque and is chosen for the baseline system.

TABLE 1: GENERATING SYSTEM SPECIFICATIONS

- 4400 kW Nameplate Rating
- 25 Percent overload for a period of one hour per day
- 6600 V Terminal Voltage
- Class B Insulation
- Drip proof enclosure
- 3300 ft altitude
- Across the line starting
- Self-starting capability
- 1.37 per unit limitation on drive train torque for frequent occurrences
- Minimum starting torque 77,000 lb-ft

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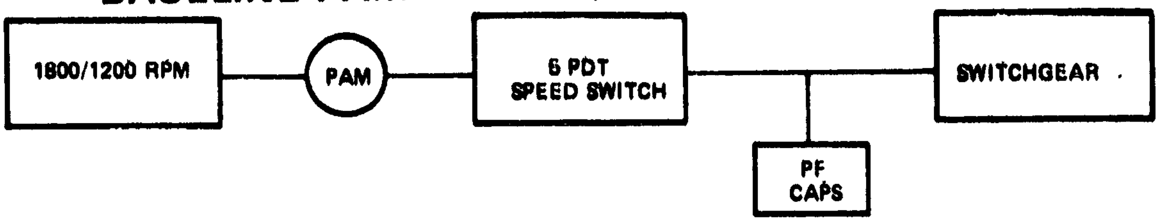
The cost, size, and weight of the components for the baseline PAM system are shown for a 6600 V system in Figure 4. All costs are based on the 100th unit of a 1,000 unit production run in 1977 dollars.

BASELINE PAM SYSTEM,DIAGRAM AND COSTS



	GENERATOR	SPEED SWITCH	CAPACITORS	SWITCHGEAR	TOTAL
*COST, $	99,463	6,212	5,700	19,654	131,029
SIZE, m	9612 FRAME (6600V)	36 x 34 x 12 x 77	60 x 60 x 60	83 x 40 x 102	
WxLxH, m	61½ x 91½ x 76				
WEIGHT, LBS.	27,505	1,375	1,375	3,000	33,255

*1977 DOLLARS

Figure 4

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VARIABLE SPEED SYSTEM DESIGN

For this study, consideration was limited to conventional single rotor doubly fed machines with solid state converters. Two types of converters were evaluated: a bidirectional cycloconverter and a unidirectional rectifier-inverter slip power recovery system. The basic configuration for the cycloconverter system is illustrated in Figure 5. The stator of the wound rotor induction machine is tied to the interfacing utility network through a starter which consists of a three-pole contactor, current limiting fuses and the protective relaying required to protect both the wind turbine generating system and the interfacing utility network.

SIX-PULSE MIDPOINT CYCLOCONVERTER

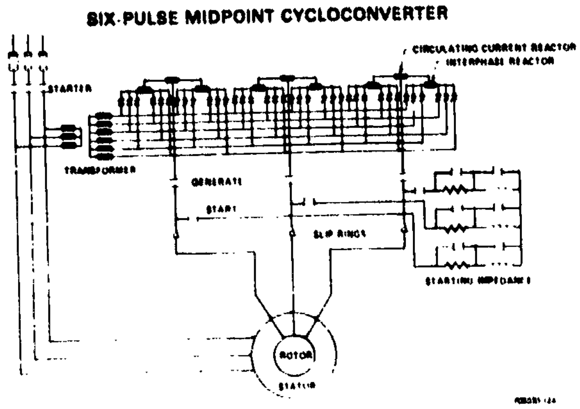


Figure 5

The rotor leads are brought out of the machine through slip rings. Starting impedance and associated contactors are provided in those instances where the wind energy system must be started with the machine in the motoring mode to accelerate the blades to a point where the wind is capable of bringing it within the operating range. Startup as a motor for a doubly fed machine configuration results in relatively low inrush current since the starting impedance can be tailored to the desired characteristics.

In the generating mode the rotor circuit is isolated from the starting impedance and connected, through contactors, to either a cycloconverter or a rectifier inverter depending upon the doubly fed concept utilized. The cycloconverter acts as a frequency changer and provides for power flow both to and from the rotor. When the generator input is less than synchronous speed power flows to the rotor while generator input above synchronous speed results in power flow from the rotor. The rectifier inverter utilized in a slip power recovery system is active only when the generator input is above synchronous speed. The rectifier inverter rectifies the rotor output then inverts it to 60Hz for compatibility with the interfacing network.

Due to the machine winding ratio the rotor voltage is less than the stator voltage. As a result, the voltage level on the 60Hz side of either the cycloconverter or the rectifier inverter is significantly less than the network voltage and a step up transformer provides the interface to the network.

Cycloconverter Design

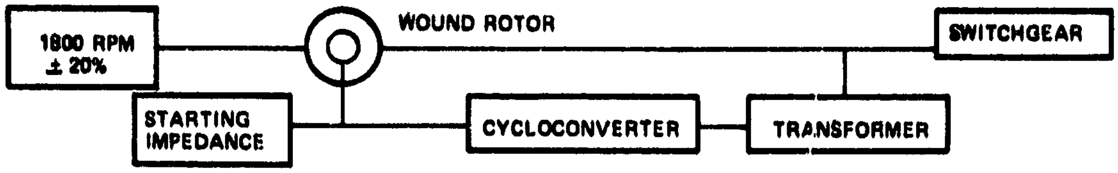
Basic cycloconverter designs are available for three, six and twelve pulse systems. In its conceptual designs Westinghouse eliminated all three pulse systems as probably being too rich in undesireable frequencies. The twelve pulse circuits were eliminated since they were considered to be too costly. Among possible circuit configurations, transformer utilization favors a six pulse midpoint cycloconverter configuration as the baseline design. The fundamental specifications for this system are illustrated in Table 2.

TABLE 2: VARIABLE SPEED SYSTEM SPECIFICATIONS

PARAMETER	SYSTEM RATING
System Rated Power	4.4MW
Wound Rotor Machine	4000hp
Synchronous Speed	1800rpm
Speed Range	± 20%
Primary Voltage	6600V, 3 Φ, 60Hz
Secondary Voltage - Open Circuit	1650V, 3 Φ
Cycloconverter Output Frequency	+12Hz through Zero, to -12Hz
Commutation	Line Commutated
Cycloconverter Design	6 Pulse Midpoint

Data shown on Figure 6 for the cost, size and weight of the principal generating system components reflect costs in 1977 dollars and the scenario of the 100th unit of a 1000 unit production run.

BASELINE VARIABLE SPEED SYSTEM DIAGRAM AND COSTS



	GENERATOR	CYCLOCONVERTER	STARTING IMPEDANCE	TRANSFORMER	SWITCHGEAR	TOTAL
*COST, $	126,336	74,038	6,825	8,500	19,654	235,353
SIZE, m	9611 FRAME	48 x 160 x 100	40 x 30 x 90	60 x 60 x 84	83 x 40 x 102	
WxLxH, m	61½ x 83 x 76					
WEIGHT, LBS.	23,660	8,400	2,500	9,400	3,000	46,960

*1977 DOLLARS

Figure 6

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WIND TURBINE GENERATOR SIMULATION

A complete Wind Turbine Generator model has been implemented on a Westinghouse hybrid computer to evaluate alternative electrical generator systems. Basically, the non-linear items are implemented on the analog consoles while the control and integration features of the model are programmed into the digital portion. The drive train is composed of a blade, a low speed shaft, a gearbox, and a high speed shaft which drives the rotor of the generator. A transmission line network provides system voltage. Generator parameters, namely rotor and stator impedances, are generated in real-time as a function of the slip. A simple cycloconverter simulation provides rotor voltage. Digital computer routines determine wind conditions, speed, torque compensation, and other control commands. The aerodynamic rotor is represented in a simplified fashion by means of a digital computer routine which accepts wind speed input and calculates the wind torque using the C_p relation of Figure 1. The curve is extrapolated for high velocity ratios to assume negative values to simulate drag under startup and transient conditions.

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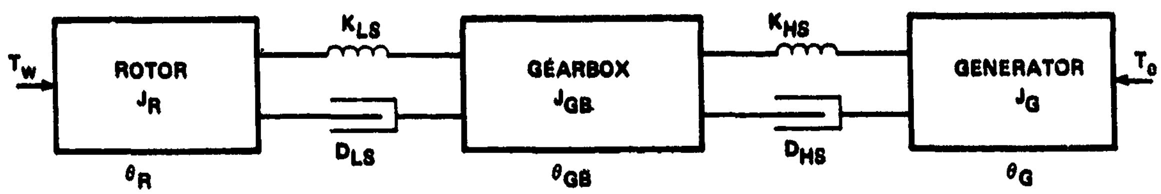
The 2-p perturbation caused by wind shear effects is modeled on the analog console as a sinusoidal wind torque variation with an amplitude of +25 percent of the wind torque itself. It is added to the output of the wind torque subroutine. Its frequency is determined by the blade speed and changes continuously as the blade speed varies.

The mechanical dynamics of the drive train are simulated as illustrated in Figure 7. The hybrid computer implementation of the model includes drive train efficiency and friction.

MECHANICAL DYNAMICS MODEL OF THE DRIVE TRAIN



$$J_R \ddot{\theta}_R = T_w + K_{LS}(\theta_{GB} - \theta_R) + D_{LS}(\dot{\theta}_{GB} - \dot{\theta}_R)$$

$$J_G \ddot{\theta}_G = -T_e + K_{HS}(\theta_G - \theta_{GB}) + D_{HS}(\dot{\theta}_G - \dot{\theta}_{GB})$$

$$J_{GB} \ddot{\theta}_{GB} = K_{LS}(\theta_{GB} - \theta_R) + D_{LS}(\dot{\theta}_{GB} - \dot{\theta}_R) + K_{HS}(\theta_G - \theta_{GB}) + D_{HS}(\dot{\theta}_G - \dot{\theta}_{GB})$$

Figure 7

Both 2-speed PAM and variable speed synchronous flux generators are modeled as polyphase induction machines. Generator voltages, current and fluxes are represented in a transformed d-q coordinate system which rotates synchronously with the stator field. The generator parameters, rotor resistance, rotor inductance and stator inductance, are allowed to change with slip. They are generated through a digital computer routine. Separate 4 and 6-pole models are switched in and out by digital control to simulate the two speed PAM. The cycloconverter is controlled so as to vary the rotor voltage in accordance with a control algorithm. Such action produces variations in the generator speed aimed at controlling and stabilizing electrical power output.

SIMULATION RESULTS

The 2-speed PAM generator configuration was simulated in a number of hypothetical operational situations and found to be very tractable for wind turbine application. Figures 8 and 9 represent a combination of startup, steady state, and speed switching transients. Turbine speed is fully controlled by the electrical generator with no active pitch or other aerodynamic devices. The following sequence of events is illustrated.

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1. Motoring from zero speed in a 6 pole configuration (wind speed = 19 mph).
2. Termination of motoring when the wind torque reaches a 0.1 pu value (Approx. 600 rpm).
3. Aerodynamic acceleration to 1,200 rpm.
4. Steady state generating operation at 1,200 rpm (6 pole).
5. Wind speed increase to 25 mph to trigger pole switching.
6. Generator excitation removal upon pole switch command.
7. Aerodynamic acceleration to 1800 rpm.
8. Return to generator excitation with a 4 pole connection.
9. Steady state generating operation at 1800 rpm.
10. Wind speed decrease to 19 mph to trigger pole switching.
11. 4 pole to 6 pole switch command.
12. Removal of generator excitation for 2 second.
13. Speed increase of approximately 2% (aerodynamic operation) at the end of the 2-second delay.
14. Return to generator excitation with a 6 pole connection.
15. Generator forces deceleration.
16. 14 mph wind gust overcomes generator torque and speed exceeds 1800 rpm.
17. 6 pole to 4 pole switch command.
18. Generator torque sufficient to control speed.
19. Gust subsides - 4 pole to 6 pole switch command.
20. Generator forced deceleration to 1200 rpm.
21. Generator steady state operation at 1200 rpm.

Figures 10, 11, and 12 show typical results obtained from the dynamic simulation of a baseline variable speed wind turbine generator. Figure 10 shows the effect on wind torque produced by a gusty wind and the two per revolution blade shear effects. The figure shows that the rotor excitation can be controlled, through the cycloconverter, to produce a nearly constant power output under the

PAM STARTUP AND POLE SWITCHING TRANSIENT WITH WIND GUST

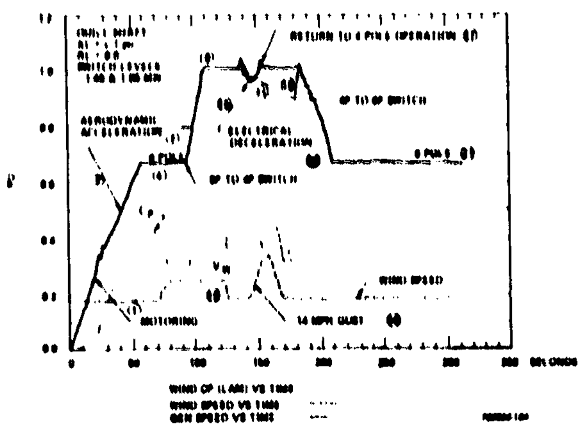

Figure 8

PAM GENERATOR POWER,TORQUE,AND WIND TORQUE STARTUP AND POLE SWITCHING WITH GUST

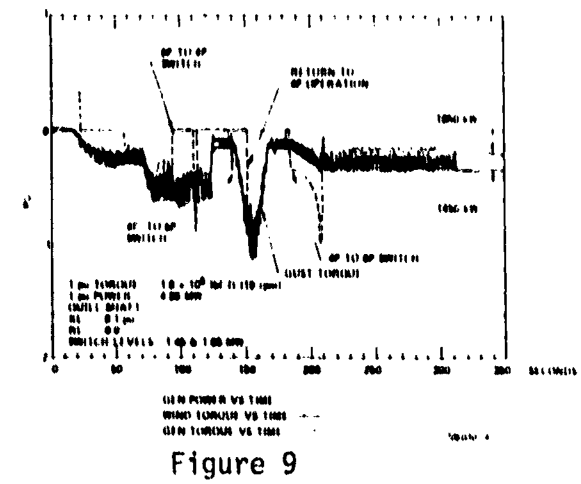

Figure 9

BASELINE VARIABLE SPEED GENERATOR RESPONSE TO WIND TURBINE TORQUE

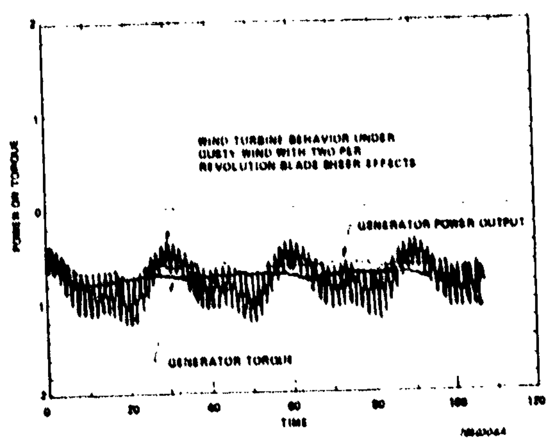

Figure 10

UNCOMPENSATED VARIABLE SPEED GENERATOR SYSTEM RESPONSE TO WIND TURBINE DRIVE TRAIN RESONANCE

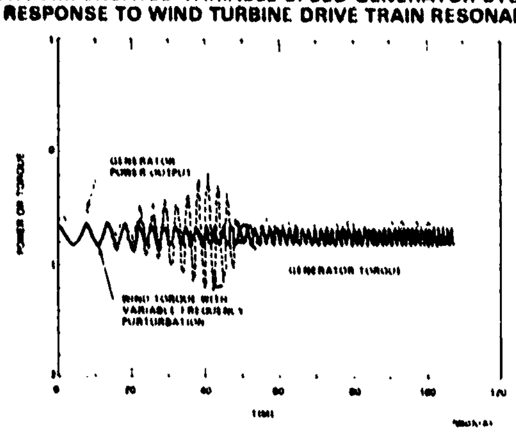

Figure 11

BASELINE VARIABLE SPEED GENERATOR SYSTEM RESPONSE TO WIND TURBINE DRIVE TRAIN RESONANCE

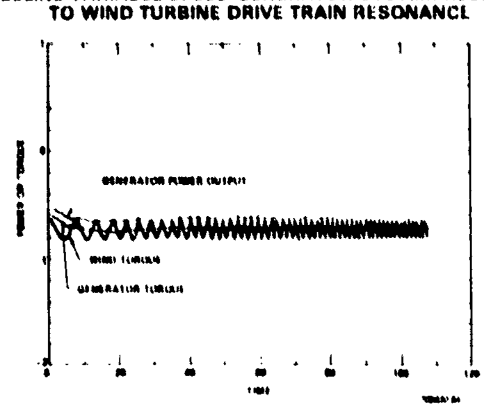

Figure 12

severe wind torque conditions. Figure 11 shows a transient that, by means of varying frequency perturbation on the wind speed, triggers a drive train natural resonance. The resonance is clearly visible and is obtained without making an attempt to compensate for it through the rotor circuit. Figure 12 shows the same transient when variable speed compensation is fully applied. It is seen that the resonance is completely eliminated.

CONCLUSIONS

Both 2-speed PAM and variable speed baseline generator systems offer attractive benefits to wind turbine performance. Table 3 summarizes the relative advantages and disadvantages of each. Final selection of a generator system, however, must be made in the context of an overall wind turbine design. Table 4 illustrates a generator system selection process. The findings conclude that 2 speed PAM is preferable to single speed provided that further evaluation of switching transients uncovers no adverse impact. The variable speed option is preferred over both single and two-speed if the project schedule allows final development. These conclusions could differ for other wind turbine gearbox and/or blade control configurations.

REFERENCE

1. T. S. Andersen, H. S. Kirschbaum, Multi-Speed Electrical Generator Application to Wind Turbines, AIAA paper 80-0635-R presented at AIAA/SERI Wind Energy Conference April 10, 1980. J. Energy Vol. 5, May-June 1981, pp. 172-177.

TABLE 3: PAM vs. DOUBLY FED MACHINE WITH CYCLOCONVERTER

PAM GENERATOR

- ADVANTAGES
  - LOWER COST
  - MINIMUM OF TOWER SLIP RINGS/CABLING
  - SIMPLER SYSTEM, REQUIRES LESS MAINTENANCE
  - MORE RELIABLE
  - STANDARD PRODUCT
  - SIGNIFICANT EXPERIENCE IN MOTORING MODE
  - LOWER HARMONICS

- DISADVANTAGES
  - TWO SPEEDS
  - LIMITED DAMPING OF TWO PER REVOLUTION PERTURBATION
  - POWER FACTOR CONTROL IN DISCRETE STEPS
  - INRUSH CURRENT AT POLE SWITCHING

DOUBLY FED MACHINE

- ADVANTAGES
  - ELIMINATION OF TWO PER REVOLUTION PERTURBATIONS WITH AND WITHOUT QUILL SHAFT
  - CONTINUOUS SPEED CONTROL OVER THE OPERATING RANGE
  - GUST AND TRANSIENT SMOOTHING
  - MINIMUM OF DRIVE TRAIN COMPONENTS, PERMITS ELIMINATION OF QUILL SHAFT
  - LOW INRUSH MOTOR STARTING, STARTING IMPEDANCE TAILORED TO DESIRED CHARACTERISTICS
  - VERSATILE POWER FACTOR CONTROL
  - MINIMUM TOWER WEIGHT, REDUCED MACHINE SIZE
  - BEST VARIABLE SPEED CONCEPT
  - BEST ANNUAL ENERGY CAPTURE
  - ELIMINATION OF DRIVE TRAIN RESONANCE
  - 96.5 PERCENT EFFICIENT AT FULL LOAD

- DISADVANTAGES
  - GENERATOR OPERATING AT 20 PERCENT ABOVE SYNCHRONOUS SPEED
  - ADDITIONAL HARDWARE AT TOWER BASE
  - HIGHER COST
  - ADDITIONAL TOWER SLIP RINGS/CABLING
  - HARMONIC DISTORTION (UNDER 5 PERCENT THD)
  - ADDITIONAL LEAD TIME
  - GENERATOR SLIP RINGS

TABLE 4: ELECTRICAL GENERATOR SYSTEM TYPE EVALUATION FOR WIND TURBINE APPLICATIONS

TYPE	ADVANTAGES	DISADVANTAGES	SELECTION BASIS	FINDINGS
SINGLE SPEED	• Low Cost • Simplicity	• Low Energy Capt. • Low Adaptability	• Does cost benefit overcome performance penalty?	No
MULTI SPEED	• Better Energy Capture • Stepwise Adaptability	• Some Transients and losses during switching	• Are switching transients acceptable?	Probably, but uncertain
VARIABLE	• Best Energy • Minimum Startup and speed change transients or losses	• Real but limited Direct Experience • Relative High Cost	• Do performance advantages outweigh cost?	Yes
			• Is successful development ultimately assured?	Yes
	• Continuously Adaptable • Provides all necessary Drive Train Damping.	• Development Required • More complex structural dynamics	• Can required development be achieved within commercial wind turbine budget and schedule?	No Supported Development required
			• Can remainder of wind turbine accommodate variable speed?	Yes