VARIABLE-SPEED WIND SYSTEM DESIGN

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In addition, Reuland Electric Co. of Industry, CA, investigated the technical feasibility of a DFM design from a choice of three possible sets of specifications and provided the cost-calculations for this design.

1. SUMMARY

Almost from the onset of the development of wind energy conversion systems (WECS), it was known that variable-speed operation of the turbine would maximize energy capture. In the past, variable-speed operation was not an option due to the fact that available technologies were either too expensive to implement or too unreliable during operation. Engineering efforts therefore focused on maximizing the energy capture through the use of variable-pitch blades or the optimization of fixed-pitch blades. With the advancement of power electronics, the obstacles to variable-speed operation were substantially reduced.

This study was commissioned by the Bonneville Power Administration to assess the cost, efficiency gain, reduction of the cost of energy (COE), and other operating implications of converting the existing hardware of a modern fixed-speed wind energy conversion system to variable-speed operation.

The purpose of this study was to develop a preliminary design for the hardware required to allow variable-speed operation using a doubly-fed generator with an existing fixed-speed wind turbine design. The turbine selected for this study is the AWT-26 designed and built by Advanced Wind Turbines Inc. of Redmond, Washington. This choice is a recent turbine design which exploits the latest technologies available for the mechanical part of the turbine. The doubly-fed generator topology was chosen because it promises the lowest cost implementation of all topologies available, yet offers operational features which other known variable-speed topologies could offer only at additional cost. These features include power factor control at the utility interconnection point, constant-torque start-up of the turbine, and non-dissipative damping of output power oscillations to reduce stresses on all mechanical components. The cost reduction inherent to this topology is mostly due to the possible de-rating (up to 50%) of both the generator and the power electronic converter. The lowest projected COE using this variable-speed generation system is projected to be \$ 0.0499/kWh, compared to the lowest possible COE with fixed-speed generation which is projected to be \$ 0.0546/kWh. This translates into a 8.6% reduction of the COE using this particular variable-speed generation option.

The preliminary system design has advanced to the point where the printed circuit boards can be physically laid out based on the schematics developed, and the system software can be written based on the control flow-charts presented. The core of both hardware and software has already been proven to be successful in earlier versions of VSG systems using doubly-fed generators and resonant power converters with combustion engines as prime movers.

2. INTRODUCTION

The exploitation of renewable energy sources such as wind, photovoltaics, and hydro has received varying attention over the past decades. Whereas the technological development of hydro-power is by far the most advanced due to its vast energy content, the other two energy sources have been receiving increasingly more attention recently. This is partly due to the fact that the siting of additional hydro-projects has become difficult, if not impossible. On the other hand, the cost of energy (COE) for wind and photovoltaics has steadily decreased. For wind power, in particular, the COE is becoming comparable to that of power generated by burning fossil fuels.

The purpose of this study was to define a preliminary design for a variable-speed wind generation (VSWG) system using a doubly-fed generator [1] and an advanced resonant power converter [2]. Based on this design the increased energy capture of the system was to be determined and compared to that of the fixed-speed wind generation (FSWG) system. Using preliminary cost information for the VSWG system, the cost of energy (COE) was to be compared to its FSWG counterpart. Both the hardware and software developed for this application rely on hardware and software already developed and successfully demonstrated in earlier studies of variable-speed generators using reciprocating engines as prime movers [3]. The level of design has advanced to the point where all control elements of the VSWG system will be integrated on a single micro-controller circuit board.

This preliminary design is based on the assumption that a utility-scale wind-turbine like the AWT-26, manufactured by Advanced Wind Turbines, Inc., is being retrofitted. A follow-up contract [4] with the National Renewable Energy Laboratory (NREL) is being negotiated, as this study comes to a close, to fund the actual retrofit effort. For a different type of wind-turbine, the design parameters for the generator and power electronic converter will change. However, the general control algorithms would not likely be affected for a different type of wind-turbine.

The body of this report presents the results of the VSWG system development. Operation under normal and fault conditions is described in detail, the system performance for variable-speed operation is estimated and compared to the original fixed-speed system performance, and specifications for all system components (generator, power electronic converter, and system controller) are given. Costs for all components are estimated, and incremental system cost is compared to incremental energy production. Finally, operational features of the VSWG which are not available in the existing FSWG system are outlined.

3. STUDY RESULTS

3.1 Operating Conditions Evaluated

The following is the operational description of the VSWG system using a doubly-fed machine (DFM) with its associated controls, operating under normal and abnormal (fault) conditions. All steps are to be executed in sequence as listed. Refer to Figure 3.1.

3.1.1 Normal Operating Conditions

Start-up/Normal Operation/Shut-down (CB1 always closed):

Start-up:

- Close S_R , synchronize DFM to the grid at 0 RPM with CB2.
- Release parking brake.

VSG operation under varying wind conditions:

- Adjust RPM as determined by the RPM-controller (see Chapter 3.3.3).

Shut-down:

- Ramp down $i_{r,ref}$ to 0, stop USRC.
- Open CB2.
- Upon confirmation that CB2 is open, open S_R and (simultaneously) instruct AWT-26 controller to deploy the blade tip brakes (0.03 sec or less after initial shut-down command was given).

3.1.2 Abnormal Operating Conditions

Emergency shut-down caused by any of the following conditions:

Manually Triggered Emergency Shut-down:

- Ramp down $i_{r,ref}$ to 0, stop USRC.
- Trip CB2.
- Upon confirmation that CB2 is open, open S_R and (simultaneously) instruct AWT-26 controller to deploy the blade tip brakes (0.03 sec or less after initial shut-down command was given).
- Open CB2.

USRC failure (only):

- Open S_R .
- Trip CB2.
- Upon confirmation that CB2 has opened, instruct AWT-26 controller to deploy the blade tip brakes (0.03 sec or less after fault detection).
- Open CB2.

FIGURE 3.1: VSWG CONTROL BLOCK DIAGRAM

- CB1 VSWG SYSTEM MAIN CIRCUIT BREAKER (LOCATED IN AWT-26 CONTROL ENCL.)
- CB2 DFH STATOR CIRCUIT BREAKER
- S_R ROTOR CONTACTOR
- LPI, GFR LINE-PROTECTION AND GROUND-FAULT RELAYS (LOCATED IN AWT-26 CONTROL ENCL.)

AWT-26 Turbine Controller

EPC Inc.		
Corvallis, OR 97330		
Title		
VSWG CONTROL BLOCK DIAGRAM		
Size Document Number		
B	FIGURE 3.1	REV
Date: October 12, 1993 Sheet 1 of 1		

Designed by: CW
Drawn by: MZ

Utility grid failure only:

Any condition of the utility grid which exceeds the $\pm 10\%$ tolerance limits of the normal utility voltage will be considered as a utility failure. System shut-down will be triggered by the line-protection relay (LP1). This includes voltage and phase imbalances, phase-to-phase faults (single-phase and 3-phase), over- and under-voltage as well as over- and under-frequency; the ground-fault relay triggers system shut-down due to phase-to-ground faults (single-phase or three-phase).

- Upon detection of a utility grid failure, always trip CB1 and shut down the USRC (the AWT-26 controller trips CB1 under these conditions already).
- Trip CB2.
- Open S_R and (simultaneously) instruct AWT-26 controller to deploy the blade tip brakes (0.03 sec or less after fault detected).
- Open CB2.

Multiple reclosure of breaker on utility system:

- To be treated as utility grid failure with the following stipulation:
The system is to remain shut-down until a normal and undisturbed utility grid voltage has been detected for a period of time which exceeds the reclosing interval of the breaker in question by two to three times and allows for cooling of the mechanical brake by a sufficient margin.

USRC and utility grid failure:

- Upon detection of the USRC failure proceed as stated above.
- Upon detection of the utility grid failure trip CB1 (AWT-26 controller already does).

VSWG Controller failure:

- A watchdog-timer inside the micro-controller system continuously monitors system operation. Should the system controller cease operation (resulting in the loss of all control functions), the watchdog-timer will reset the micro-controller, resulting in the opening of all contactors and breakers, and the instruction of the AWT-26 controller to deploy the blade tip brakes (0.002 sec or less after fault detection).

DFM over-temperature:

- Go through normal shut-down process.

DFM loss of synchronism:

- Ramp down $i_{r,ref}$ to 0 and shut down USRC.
- Trip CB2.
- Upon confirmation that CB2 has opened, open S_R and instruct AWT-26 controller to deploy the blade tip brakes (0.03 sec or less after fault detection).
- Open CB2.

Transmission line over-/under-voltage:

The VSG system will be designed to operate without limitations at the nominal utility grid voltage $\pm 10\%$. If the utility grid voltage exceeds the nominal voltage $+10\%$ for longer than a specified period of time the USRC will shut down. The VSG system then has to shut down as described in "USRC failure only" (see above). Instantaneous overvoltages ("spikes") will cause MOV's to go into conduction. These MOV's are placed at the input and output terminals of the USRC thus shunting dangerously high voltages away from the sensitive semiconductor switches. Unless detected by the over-voltage protection of the USRC, the USRC will continue to operate. If the utility grid voltage drops below 432 Volts for longer than a specified period of time, the system will go through a normal shut-down procedure (or, if the voltage becomes too low, it will go through the utility grid failure procedure as described above).

Transmission line over-/under-frequency:

- The line-protection relay (LP1, in the AWT-26 controller) will detect this fault-type and cause the VSWG system to shut down.

For additional protection of the mechanical system, a timer will initiate deployment of the blade-tip brakes after 0.03 sec, regardless whether or not the electrical system has completed its shut-down sequence.

To allow for cool-down of the mechanical brakes after system shut-down the following minimum shut-down periods are required:

- Normal stop: 3.0 minutes
- Hard stop: 3.0 minutes
- Emergency stop: Manual system reset required

A message will be displayed after each shut-down which is due to an abnormal operating condition. Shut-downs due to the occurrence of an emergency condition require a manual system restart. Otherwise, the system is able to restart automatically or by remote control.

A set of detailed state-diagrams showing the step-by-step transitions during normal and abnormal operation can be found in Figures A.39 through A.48.

3.2 Estimated Performance Comparison - FSWG vs. VSWG

Figure 3.2 shows the power generated by the baseline wind turbine operating at sea-level as a function of wind speed before and after it has been retrofitted with VSWG capability. At higher elevations, approximately the same curves can be attained by re-pitching the turbine blades for that specific altitude. The energy production for the pre-specified wind regime increases by 15.5 percent with VSWG. Other wind regimes, are, of course, possible. The increase in energy has been calculated to be as low as 13.0 percent in certain other cases.

At the same time, the elements of the VSWG system incur additional losses. According to the generator manufacturer, the efficiency of the doubly-fed generator should not be more than 1.0 percent lower than the efficiency of the existing fixed-speed induction generator. Due to the presence of the converter in the rotor circuit, some additional power is lost there. The converter efficiency is approximately 96 percent. Since this loss percentage would be imposed on no more than 50% of the total power generated, total losses for the VSWG system are anticipated to be 2.0 percent or less.

The retrofitted baseline system has not been fully optimized for energy production with a VSWG system. The baseline blades have been designed to produce maximum energy over a wide range of wind speeds at constant rotor RPM. Maximizing efficiency at the best tip speed ratio was not the objective. Since variable-speed operation can preserve the best tip speed ratio over the entire wind speed range, the blades could be designed to take advantage of this feature. The increase in energy capture for a variable-speed optimized blade is estimated to be in the area of 1.0 percent.

The power factor correction capacitors of the FSWG system will also cause some losses when they are connected to the grid. The losses are not related to power production, but rather to their independent charging and discharging by the AC grid. Based on typical resistance levels, as gathered from data sheets, the losses are estimated to be 0.3 percent of the total power produced. The VSWG system does not require separate power factor correction capacitors.

The soft-start equipment of the baseline wind system imposes average losses of 1.0 kW. This translates into a 0.5 percent loss of the total energy generated. The VSWG system does not require separate soft-start equipment.

Several of the other traditional loss categories might also be favorably affected by the use of VSWG system. Examples are array, downtime and blade soiling losses. The specific mechanisms involved give rise to arguments that this might be the case. However, these effects are undoubtedly small (or are insufficiently investigated to this date in order to allow a reliable quantification) compared to the primary mechanism for energy gain when using VSWG.

Optimal Variable Speed Performance

Rotor Power vs Wind Speed

Figure 3.2

Shaft Speed vs Wind Speed

Figure 3.3

Considering all of the factors described above, the net energy gain is estimated to be as follows:

Table 3.2: Net VSWG System Energy Gain	
	NREL Wind Regime (%)
Basic retrofit increase	15.5
VSWG system losses	-2.0
Further VSWG blade optimization	1.0
Soft-start losses	0.5
var compensation capacitors	0.3
Total	15.3

The above figures are defensible based on past work. However, to be conservative, the 15.3 percent total has been reduced by 2.0 percent. Possible sources of this reduction are:

- the potential existence of a wind regime that leads to a smaller basic energy gain and/or,
- potentially higher losses in the VSWG system, particularly in the converter.

Finally, the value of var-generation should be discussed. The VSWG system being designed needs no reactive power compensation and can generate var's for the compensation of other loads or generators on the grid. The value of this feature is a strong function of the stability of the local grid. If, for example, the power factor were poor due to the presence of uncompensated fixed-speed wind systems or motors, the value of var-generation would be high. If the local power factor were quite acceptable, the value could be zero. In general, the local utility grid can be expected to be in need of reactive power due to the presence of induction motors and the inherent inductance of transmission and distribution lines. All utilities impose strict power factor requirements on all significant loads and generators for this reason. In spite of that, utilities often need to install individual phase power-factor correction capacitors as a remedial measure. Therefore, some value can be assumed even though it is difficult to quantify.

3.3 Preliminary Specifications

3.3.1 Doubly-fed Machine

From the wind-turbine performance curves (Figures 3.2 and 3.3) the operating point was found which determines the rating of the wound-rotor generator. This operating point yields maximum shaft torque and occurs at 60 RPM and 310 kW turbine output.

The following set of generator design parameters was most favorable for the given size and weight limitations:

Table 3.3.1 Doubly-Fed Generator Specification	
Hp-rating	350 hp
Number of poles	4
Service Factor	1.15
Frame Size	449T
Primary Voltage	480 Volts
Primary Current	395 Amps
Secondary Voltage	480 Volts
Secondary Current	170 Amps
Stator:Rotor Winding-ratio	1:2.5
Secondary Magnetizing Current	50 Amps
Nominal Generator Efficiency	95%
Synchronous RPM	1,800 RPM
Rotor Mechanical RPM Rating	2,500 RPM
Maximum Ambient Temperature	120°F
Maximum Generator Weight	960 kg

Size Limitations (exceed specifications for 449T frame spec):

- Overall generator width not to exceed 36 inches
- Overall generator height not to exceed 36 inches
- Generator length past rear mounting holes not to exceed 12 inches

Additional Equipment:

- Thermal switches, N.O., closing at 60°C, in each stator winding, internally connected in parallel with each other.
- Thermal switches, N.C., opening at 95°C, in each stator winding, internally connected in series with each other.
- J-type Thermo-couples in each stator winding.
- The generator is forced cooled with an external fan (no shaft-mounted fan).
- Shaft-mounted RPM-Encoder (output A: 240 pulses/rev; output B: 1 pulse/rev.).

The mechanical design of the wound-rotor generator will differ from the design of the existing fixed-speed generator as follows. The wound-rotor generator will be of the "TEFC"-type (totally enclosed, fan-cooled). This design is slightly more costly than the existing open-type induction generator, however the use of the TEFC-type machine in this particular application offers the following advantages:

- No dust is able to enter the interior of the generator which otherwise could cause damage to the slip-rings, brushes, end-windings, bearings, and the airgap. The replacement-interval of the brushes thus may reach several years.
- Condensation will not likely occur inside the generator; therefore, the otherwise necessary space-heater can be eliminated.
- Due to the above mentioned dust-damage, open-type generators have to be dismantled and rewound after a certain number of years in service. This interval will be greatly extended through the use of the TEFC-design.
- Due to the controlled cooling-approach the generator will be operating within a narrow temperature range. No mechanical losses due to a shaft-mounted fan are incurred. The electrical fan will operate only if cooling of the generator is needed. No estimates exist on how much energy savings would result from this approach.

3.3.2 Power Electronic Converter

Corresponding to the above specification for the doubly-fed generator, the following specification for the power electronic converter results:

Table 3.3.2 Resonant Power Converter Specification	
Rated Output Power	150 kVA
Rated Input Voltage	480 Volts ($\pm 10\%$)
Rated Output Voltage	480 Volts
Rated Output Current	180 Amps
Output Frequency Range	DC to 65 Hz
Converter Efficiency	$\geq 96\%$
Maximum Ambient Temperature	120 °F

Additional requirements:

- Total harmonic distortion on both the grid-side and the load-side of the converter has to satisfy ANSI/IEEE 519 requirements.
- The power-factor on the grid-side of the converter has to be adjustable between 0.9 leading and 0.9 lagging at rated output power.

The type of power electronic converter considered most suitable for this application is the Unipolar Series Resonant Converter (USRC) as developed by EPC under separate engineering contracts.

The USRC excels over other possible converter-types such as line-commutated inverters, cyclo-converters or PWM-type inverters in terms of efficiency, utility-line harmonics, output-frequency range, and cost.

3.3.3 Variable Speed Generation Controls

The VSWG system can be subdivided into two sections, power and control (Figures 3.1 and A.1):

- Power Section:

The hardware required to interconnect and protect the doubly-fed machine, the Unipolar Series Resonant Converter and the utility grid.

- CB1:
VSWG system circuit breaker, rated at 125% of rated system current, equipped with a shunt trip coil to disconnect the VSWG system from the utility if certain utility-fault conditions are detected (located inside the AWT-26 control enclosure, Figure A.2).
- CB2:
Stator circuit breaker of the doubly-fed generator; rated at 125% of the rated stator current; equipped with an electric operator for automatic closure and opening, a shunt trip coil to trip during certain fault conditions and a set of auxiliary contacts to indicate its status to the micro-controller system.
- S_R :
Rotor contactor, located between the output of the USRC and the rotor terminals of the doubly-fed generator; used to disconnect the rotor of the doubly-fed generator during certain fault conditions.
- Line-protection Relays:
The line-protection relays are connected between CB1 and the VSWG system (located within the AWT-26 controller enclosure, Figure A.2); they consist of a line-protection relay which trips on over-/under-frequency and/or over-/under-voltage conditions, as well as a ground-fault relay which trips if the vector sum of all line-currents does not equal zero at any time.
- Control Transformer:
480/120VAC step-down transformer rated at 2.0 kVA to supply all control power to the VSWG controller from the 480 VAC line.
- Control section:

The micro-controller printed circuit board and its associated power supplies, relays and sensors required to control the components of the power section, and the hardware required to interface with the AWT-26 system controller.
- Micro-controller PCB:
80C196-based single-board micro-controller system (for circuit diagrams see Figures A.12 through A.26), used to control all functions of the VSWG system as well as establishing the interface between the VSWG system and the AWT-26 controller; integrated are all interface circuits required for analog and digital input from VSWG system sensors as well as interface circuits required to operate all contactors and breakers within the power circuit and control the USRC.

- **Synchronizing Detector PCB:**
Opto-isolated 3-phase zero-voltage sensors connected in parallel with each phase switch of CB2 to sense the simultaneous zero-voltage condition on all 3 phases required before CB2 is allowed to be closed (Figure A.4); will not allow closure of CB2 if incorrect phase sequence exists.
- **P/Q-measurement PCB's:**
Active/reactive power sensors used to measure active/reactive power on the stator of the doubly-fed machine and at the VSWG system interconnection with the utility grid (see Figures A.8 through A.11). Also available from these boards are scaled-down line-voltage signals and line-current signals which are used by the micro-controller for VSWG system monitoring purposes.
- **AWT-26 Controller Interface:**
Signal interface between the AWT-26 turbine controller and the VSWG system controller (Figure A.3); signals sent from the AWT-26 turbine controller to the VSWG system controller are System Start/Stop (dry contact), CB1/Trip (dry contact), Emergency Stop (dry contact) and target RPM (4-20 mA loop); the signal sent from the VSWG system controller to the AWT-26 turbine controller is Emergency Stop/Deploy Blade Tip Brakes (dry contact).
- **VSWG System Control Software:**
Preliminary block diagrams describing the system control software are in Appendix A (Figures A.27 through A.38). The major run-time logic routines are also shown in the VSWG control block diagram (Figure 3.1). A description of these routines follows.
 - **Contactor/Breaker Controller and Fault Logic:**
Supervising and changing the status of all system contactors and breakers during normal operation; assures safe system shut-down under all fault conditions.
 - **RPM Stabilizer Logic:**
Using instantaneous generator RPM as input this logic superimposes small changes onto the rotor current frequency reference signal to the USRC. These highly dynamic but very small frequency adjustments result in very stable generator operation and also provide dynamic system damping without dissipating energy in resistive components (non-dissipative damping).
 - **RPM Controller Logic:**
The RPM controller logic determines the steady-state value of the rotor current frequency reference based on the target-RPM input from the AWT-26 turbine controller.

Q_s -Controller Logic:

The stator reactive power (Q_s) controller logic dynamically adjusts the rotor current amplitude reference supplied to the USRC to maintain a preset value of reactive power supplied from the generator stator to the utility grid ($Q_s \geq 0$), or drawn by the generator stator from the utility grid ($Q_s < 0$).

3.3.4 Effect of Brushless Doubly-fed Machine (BDFM) on VSWG Specifications

The existing data and the design expertise gained on the BDFM-design to date do not allow projections on how the VSWG specifications will be affected by the use of a BDFM at the 300 kW power level. This part has to remain subject of future work.

3.4 Cost Estimates

3.4.1 Doubly-fed Machine (DFM)

The DFM (optimized for the application) is estimated to cost about the same as the presently used induction generator of the baseline wind system (\$ 7,000). This assumption is based on the following:

- Production cost of electrical machines depends to a large degree on the weight of the machine (which represents the value of copper and iron used). The manufacturer which supplied the cost estimates indicated that the weight of the DFM (4-pole, 350 hp) will not exceed the weight of the induction generator which is currently being used.
- Volume purchasing.

3.4.2 Power Electronic Converter

The power electronic converter is estimated to cost \$60 per kVA of converter rating. Component lists with prices for resonant converters have been prepared on numerous occasions by EPC. They contain hundreds of components and cannot all be identified here. The cost of manufacturing the converter has also been analyzed by a major electrical supplier that manufactures converters of this rating. The \$60/kVA figure is believed to be a reasonable selling price, taking into consideration all of the factors which would be present in selling the VSWG system in volume. Since the rating of the converter is 150 kVA, the total converter cost would be about \$9,000.

3.4.3 Controls

Table 3.4.1 lists the VSWG power control hardware cost. The total cost for this is estimated at \$5,920. Table 3.4.2 lists the VSWG signal processing hardware cost, including the VSWG micro-controller printed circuit board. The estimated cost of the signal processing hardware totals \$2,610.

3.4.4 VSWG System with BDFM

In the absence of design specifications for the BDFM-implementation no cost estimates for this effort can be made. This effort will be part of future work to be addressed later.

ITEM	QTY	PART DESCRIPTION	PART REFERENCE	MFGR/PN	UNIT COST	AMOUNT
1	1	CB,600A,3-PH,600V,SH.TR.,AUX.SW.	CB1	ABB/MSB62600L+SM4+AM	\$715.20	\$715.20
2	12	FUSE HOLDER, 3-PHASE, 600V, 30A	F3-14	LITTELFUSE/571007	\$2.70	\$32.40
3	2	FUSE, 4.0A, 600V, SLOW-BLOW	F1-2	LITTELFUSE/FLQ4	\$3.80	\$7.60
4	12	FUSE, 0.1A, 600V, SLOW-BLOW	F3-14	LITTELFUSE/FLQ1/10	\$4.25	\$51.00
5	3	TERM.BLK, 1-PH, 600V, 20A	TB4,5	BUCH/0725/0730	\$0.94	\$2.82
6	2	TERM.BLK, 3-PH,1 4/0	TB2,3	ILSCO/PDB-11-4/0-3	\$16.80	\$33.60
7	1	CONTROL XFMR, 480V/120V, 2.0KVA	T1	ACME/TA281219	\$102.50	\$102.50
8	1	FUSE KIT, PRI, 2-PHASE, 600V, 30A	F4,5	ACME/PL-112705	\$10.45	\$10.45
9	2	CONTACTOR,NEMA 4,190A,3-PH,120V	SR,SST	ABB/EH160C-1	\$510.00	\$1,020.00
10	1	CB,500A,3-PH,600V;EL.OP.;SH.TR	CB2	ABB/MSB62500L+MM4+SM	\$1,133.80	\$1,133.80
11	4	FAN KIT, 240 CFM, 120VAC	FAN1-4	HOFFMAN/A-PA6AXFN	\$93.40	\$373.60
12	6	CURRENT SENSOR, 500A	KVAR & KW	LEM/LT500-S	\$108.60	\$651.60
13	2	CIR.BRKR, 10.0A, 2-PH, 120VAC	CB3,4	ETA/3120-F321-P7T1-R15L	\$15.32	\$30.64
14	15	WIRE, 400 MCM, 600V, STRANDED	-	/THHN	\$2.25	\$33.75
15	50	WIRE, 4/0 AWG, 600V, STRANDED	-	/THHN	\$1.15	\$57.50
16	1	ENCLOSURE, NEMA 12, 72x72x24	ENCL.1	HOFFMAN/A-727224ULP	\$1,148.00	\$1,148.00
17	1	PANEL, 72x72, PAINTED STEEL	ENCL.1	HOFFMAN/A-72P72	\$198.00	\$198.00
18	1	SWING-OUT PANEL KIT	ENCL.1	HOFFMAN/A-NADFK	\$19.19	\$19.19
19	1	TERM.BLK,3-PH,2 500MCM	TB1	ILSCO/PDB22-500-3	\$36.00	\$36.00
20	2	LATCH KIT	ENCL.1	HOFFMAN/A-L3CR	\$31.30	\$62.60
21	1	MISCELLANEOUS ITEMS	-		\$200.00	\$200.00
					TOTAL	\$5,920

Table 3.4.1: Power Circuit Bill of Materials

ITEM	QTY	PART DESCRIPTION	PART REFERENCE	MFGR/PN	UNIT COST	AMOUNT
1	1	UNINTERRUPTABLE PWR. SPLY. .9KVA	UPS	SOLA/56-300-09	\$899.00	\$899.00
2	2	POWER SUPPLY, +5, +12, -12 SW.TYPE	SPS1, SPS2	KEPCO/EFX 100T-1	\$187.00	\$374.00
3	1	POWER SUPPLY, 12V, 100W, LIN.	PS3	ELPAC/BFS 100-12	\$119.48	\$119.48
4	12	RELAY, 12VDC, DPDT	K1-12	PHOENIX/554.27.41	\$15.50	\$186.00
5	45	TERM.BLK, 300V, 15A	TB6,7,8	BUCH/0625/630	\$0.60	\$27.00
6	1	EMER. STOP PB ASY, RED	PB1	EATON/E22L2	\$7.00	\$7.00
7	1	LEGEND PLATE, "EMER.STOP"	PB1	EATON/E22N313	\$0.95	\$0.95
8	1	DUAL OUTLET 120VAC	O1	CUTLER/HAMMER	\$2.50	\$2.50
9	3	CONTACT BLOCK	PB1	EATON/E22B2	\$6.06	\$18.18
10	1	VSG CONTROLLER PCB	VSG PCB	EPC/VSG2	\$500.00	\$500.00
11	1	CUST.INFC PCB ASY, TESTED	TB2	ALTECH/5726.2	\$45.50	\$45.50
12	1	SYNCHRONIZER PCB	SYN PCB	EPC/SYN1	\$80.00	\$80.00
13	2	P/Q-MEASUREMENT PCB	PQM PCB	EPC/PQM1	\$100.00	\$200.00
14	1	MISCELLANEOUS ITEMS	-	-	\$150.00	\$150.00
					TOTAL	\$2,610

Table 3.4.2: Control Circuit Bill of Materials

3.5 Modifications to FSWG System Needed to Incorporate VSWG

3.5.1 Mechanical Modifications

Four aspects of the existing mechanical design of the AWT-26 turbine have been identified where mechanical modifications may become necessary in order to allow maximum efficiency VSWG operation (thus allowing the intended proof-of-concept retrofit).

- **Tower Stiffness:**

Due to the increase of maximum turbine blade RPM, thrust loads on the tower for certain wind-speeds are higher than thrust loads experienced during FSWG operation. Due to the planned change-over from a lattice-type tower to a tubular tower for the AWT-26 turbine, the tower stiffness is expected to be sufficient, the need for support by guy-wires is uncertain.

- **Drive Train:**

The dynamic loading of the drive train components may change during VSWG operation compared to FSWG operation. Therefore, a design review of the drive train components is deemed necessary and resulting component redesigns may have to be implemented.

- **Turbine Blade Tip Brakes:**

Due to the 30 percent increase of maximum turbine blade RPM (see Figure 3.3), the mechanical loading on the turbine blade tip brakes increases. A redesign of the blade tip brakes is deemed necessary to allow safe VSWG system shut-down during operation at higher than FSWG RPM.

- **Turbine Blade Strengthening:**

Due to the increase of maximum operating RPM for certain wind-speeds, the centrifugal forces experienced by the turbine blades in that RPM-range are higher than for FSWG operation. The blades have already survived run-away RPM which exceeded the maximum VSWG operating RPM. However, for continuous operation at these RPM-settings, the blades have to be strengthened to withstand the higher centrifugal forces.

3.5.2 Electrical Modifications

Implementation of the VSWG hardware and its associated controls requires the following modifications of the existing electrical hardware, as well as changes to the existing AWT-26 control strategy.

- Installation of the Doubly-fed Generator:

The doubly-fed generator will have the same frame-size as the existing fixed-speed induction generator. This means in particular that the foot-print of the generator and the height of the generator shaft are identical to the existing induction generator. External accessories (cooling fan, tachometer etc.) of the doubly-fed generator will be designed such that they do not interfere with other components inside the nacelle nor the nacelle-covers.

- Additional Wiring Inside the Turbine Nacelle:

Disconnect boxes will have to be provided to accommodate the power wiring of the rotor power connections, as well as additional signal connections for the tachometer, thermo-switches, and thermo-couples.

- Additional Wiring Inside the Tower:

An additional set of 3-phase power cables is required inside the tower to connect the rotor of the doubly-fed generator to its controls on the ground. Unless spare cables already exist to accommodate the additional signal wiring, an additional multi-conductor signal-cable has to be added to the existing wire harness inside the tower.

- Placement of the VSWG System Controller Cabinet:

Space has to be provided for the placement of the VSWG system controller cabinet (6' x 6' x 3'). It needs to be protected from the elements and unauthorized access, and yet have sufficient ventilation for operation at rated power and high ambient temperature.

- Redesign of the Existing AWT-26 Control Scheme to Allow VSWG Operation:

The existing control scheme of the AWT-26 controller will have to be modified to allow properly timed signal transfer between the two system control units, as well as target-RPM input from the AWT-26 controller to the VSWG system controller.

3.6 Incremental Costs vs. Incremental Energy Production

The cost estimates for the major components of the VSWG system were described in Chapter 3.4. The total cost of the unique hardware that enables VSWG is:

Table 3.6.1: Cost Estimates for major VSWG System Components	
Component	\$
Converter	9,000
Doubly-Fed Machine	7,000
Power Control Hardware	5,920
Signal Processing Hardware	2,610
Total	+24,530

On the other hand, the following hardware and the associated capital cost is eliminated or reduced by virtue of the VSWG system:

- The fixed-speed induction generator.
- The soft-start equipment that is used in the baseline FSWG system to ramp the turbine rotor promptly up to operating speed. Its \$3,300 cost can be eliminated.
- The power factor correction capacitors and their associated components costing \$1,200 can also be eliminated.
- The controller currently planned for the baseline wind system has a cost of \$2,500. Although this will not be replaced in the retrofit of the baseline wind system, in production it would be replaced by the controls listed above and the controls which are included in the converter. A more accurate production cost estimate of a VSWG system controller which completely replaces the existing FSWG system controller will be part of future work.
- The mainframe of the wind turbine rotates about the tower with shifting winds. This rotation under normal conditions may not be symmetrical; thus, the wires from the mainframe to the ground will wind up in one direction. This is corrected by a small motor operated by a controller that counts revolutions and determines when the wires must be unwound. The cost associated with this unwind system is about \$600. There is a possibility that this item can be eliminated since the mainframe could be unwound through precession by turning the turbine blades backwards with the VSWG system. However, this feature will be disregarded for now.

The VSWG system can be used to minimize the torque oscillations caused by the blade/tower interaction and to eliminate the torque spikes encountered in the transition from operation under control of the soft-start mechanism to operation "across the line". This torque control function has been regarded as one of the most important benefits of VSWG. It has been analyzed by wind system designers in detail [5] and was discussed several years ago by engineers of EPC and U.S. Wind Power, Inc., which has such a system in operation. A ball-park estimate for the capital cost benefit is \$2,000.

Finally, on the subject of capital costs, an integrated drive train should be considered. One of the design improvements that is contemplated for some wind system designs is the integration of the gearbox, generator and associated coupling, shafts and bearings into a single housing. This would reduce cost and weight. This approach generally uses a single-bearing generator. Most generators sold today are of the single-bearing, synchronous type for the engine generator market. That market passed through drivetrain integration many years ago and the product was improved substantially. The use of an induction generator might preclude the use of a single bearing, because of the extremely narrow airgap between the rotor and stator which is necessary to facilitate efficient excitation. At a power level of 275 kW, adequate clearances might not be possible to maintain the field of the induction generator. A DFM is a synchronous generator which will have a larger airgap; thus, it can be readily used with only a single bearing. This factor cannot be evaluated well today, but it might translate into a cost reduction in the years ahead when drivetrain integration takes place in wind systems.

Adding together the above factors which have been reduced to numbers gives:

Table 3.6.2: Cost of Eliminated FSWG System Components	
Component	\$
Fixed-Speed Induction Generator	- 7,000
Soft-start	- 3,300
Power Factor Compensation	- 1,200
Fixed-Speed Generation Controls	- 2,500
Mechanical Stress Reduction	- 2,000
Total	-16,000

However, VSWG causes certain capital cost increases to the non-VSWG hardware. In order to obtain the extra energy that VSWG promises, the rotor must be operated at a higher speed. This leads to an increase in thrust, which in turn leads to costs of:

Table 3.6.3: Cost of Additional Mechanical Efforts for VSWG Retrofit	
	\$
Blade Strengthening	1,500
Total	+1,500

The bottom line regarding the net increase in capital cost for VSWG is:

Table 3.6.4: Total Additional Cost for VSWG	
	\$
VSWG System Components	+24,530
Eliminated FSWG System Components	-16,000
Mechanical Efforts for VSWG Retrofit	+1,500
Total	+10,030

Operating & Maintenance Costs:

In general, VSWG should have a favorable impact on maintenance costs of the wind system as a whole due to the tight torque control that it provides. Component lifetimes should be improved. The solid-state electronics of the VSWG system itself should not incur significant maintenance costs. Both control electronics and power electronics operate virtually trouble-free in the industrial world. This should be contrasted with systems which contain a significant number of moving mechanical parts in a severe environment.

However, some perspective should be added on the types of maintenance that are anticipated for the VSWG system. Maintenance would fall into several distinct areas: the converter and control boards, the DFM and extra relays. Assuming the converter is not exposed to excessive ambient temperature or corrosive air (standard packaging techniques are available to accomodate those conditions), it would operate with the same type of maintenance record as a state-of-the-art adjustable-speed drive. While drives had a reliability problem 15 years ago, this has not been the case in recent years. Today drives operate nearly failure free at any power level. In the absence of severe abnormal occurrences, one service call in five years would seem to be a fair assumption for the controller and converter. Any repairs would take place on the ground in a single cabinet. This might translate into several hours of labor and \$300 of parts, for a total of about \$390. In large windfarms, with versatile service personnel on-site or nearby, this cost might be lower. But for the purpose of this proposal, an average of \$80 per year would seem to be reasonable.

The DFM would increase maintenance costs because of the need for periodic rotor refurbishing (cleaning, redipping and rewinding). Any induction generator would be taken to a shop for this procedure anyway. The normal maintenance cost for the fixed-speed generator might be increased by up to 20 percent. Brush inspection and replacement would be done as part of the regularly scheduled maintenance, and entail negligible cost. An annual inspection would be sufficient. Even though past experience with operating doubly-fed generators did not indicate the need for custom brush-fitting, this step may become necessary.

The VSWG system adds an additional contactor (S_p) and a breaker (CB2). They carry up to full current, however switching under normal operating conditions does not occur while the contacts carry high current. Their replacement frequency is highly dependent upon the number of times they must endure high current switching (such as during some types of emergency shut-downs). They should be inspected when the other breaker is inspected. The extent of repair is limited to the cleaning or grinding of the removable contacts.

It is being assumed that this part of the cost equation balances out.

Cost of Energy Results:

After consideration of all of the factors discussed which bear on economics, the COE of the baseline wind turbine, with and without the proposed VSWG system, using the NREL-prescribed method, is given below.

Table 3.6.5: COE Comparison FSWG vs. VSWG (\$/kWh)			
Tower Height	24.4 m (80 ft)	36.6 m (120 ft)	47.2 m (155 ft)
Baseline AWT-26	0.0593	0.0564	0.0546
With VSWG System	0.0544	0.0516	0.0499
Percent COE Reduction	8.3	8.5	8.6

The expected increment in annual energy output (AEO) is 13.3% in all cases.

3.7 Additional Operational Features with the VSWG System

3.7.1 Rotor Soft-Start

The AWT-26 FSWG system is equipped with a standard motor soft-start controller which limits inrush currents on the ac-lines as well as the associated torque transient on the drive-train.

However, the soft-start controller is unable to ramp-up RPM according to a desired torque-over-time function. Close to rated RPM, the induction generator will apply maximum (breakdown) torque to the rotor, thus unnecessarily stressing the mechanical drive-train. Immediately following this torque transient, RPM increases past synchronous speed, followed by oscillations between motor- and generator-operation (Figure 3.7.1). Once the start-up is completed, the semiconductors of the soft-start controller continuously incur electrical losses of approximately 1.0 kW for as long as the system is on-line.

With the VSWG system implemented, the following improvements of the start-up process are possible:

- The rotor can be accelerated according to an optimized torque-over-time function, thus eliminating mechanical stresses on the drive-train during start-up and also minimizing possible teeter-strikes of the rotor, and
- Once the desired operating RPM has been reached, transient system oscillations between motor- and generator-operation can be minimized.

In addition, elimination of the continuous 1.0 kW soft-start controller losses is possible during wind turbine operation (increase of 1 kWh/hr energy production during operation).

3.7.2 Non-dissipative Damping of Output-Power Oscillations

The FSWG system output power oscillates at a frequency which is proportional to rotor RPM (approximately 2 Hz for the AWT-26 system). This oscillation is due to the tower-wake which subjects the drive-train to continuous mechanical stresses. The peak-to-peak amplitude of the oscillations may be as high as 50% of the average system output power (Figure 3.7.2).

Figure 3.7.1: Low Speed Shaft Torque and Turbine RPM during FSWG Start-up

Figure 3.7.2: FSWG Generator Power and Hub-height Wind-speed

The VSWG controller incorporates a dynamic RPM-controller which provides non-dissipative damping of the output power oscillations resulting in substantially the mechanical stresses on the drive-train [5]. This may allow the designers of the mechanical system to decrease the present overrating of the drive-train components and, therefore, could reduce the cost of the overall drive-train considerably (see Chapter 3.6 and Table 3.6.2). However, it is not possible to quantify this effect until instantaneous output-power measurements of the retrofitted VSWG system are available (part of future work).

3.7.3 Reactive Power Control at the Point of Common Contact

The FSWG system is equipped with a set of AC-capacitors providing 50 kvar of reactive power which are used to compensate for the lagging power-factor of the induction generator. At low output power (25%), the overall system exhibits a power-factor of 0.93 (inductive), whereas at rated output power, the overall system exhibits a power-factor of 0.96 (inductive).

With the VSWG system implemented it will be possible to control the power-factor at the point of common contact to any desired value between 0.9 leading (capacitive) and 0.9 lagging (inductive), vs. having incremental power-factor adjustments using switched capacitor banks. This power-factor control is independent of the active output power of the VSWG system.

3.7.4 Cable Unwind Feature

The FSWG system requires periodic unwinding of the cables connecting the generator and controls in the nacelle with the system controller on the ground. This can be achieved either by manually disconnecting and then unwinding the cables or by implementing a motor drive-system in the nacelle to unwind the cables. This drive-system and its associated controller increase total system cost.

With the VSWG system the rotor-blades can be rotated opposite to normal direction of rotation while the system is off-line, and under no-wind condition. Conceptually, the resulting precession force will turn the nacelle opposite to its previous direction of turn thus unwinding the cables. Potential problems with this approach are that teeter-stop pounding occurs due to lack of aero-damping, that the precessional force may be insufficient to overcome the drag of the yaw bearing, and that the machine may be caught upwind. Once the cables would be unwound the system is ready for normal operation. The additional cost of this feature is limited to the development of the necessary micro-controller software.

BIBLIOGRAPHY

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- [2] U.S. Patent Application Serial No. 7-963386 entitled "Unipolar Series Resonant Converter", Hian K. Lauw, filed on October 14, 1992
- [3] "Variable Speed Generator Project: Comparative Performance Testing of a Genset with Synchronous and Variable Speed Generators", Advanced Energy Systems Report, Robert A. Davis (PG&E), Claus H. Weigand (EPC Inc.), Report 007.5-93.0, August 1993 prepared for Pacific Gas & Electric Co.
- [4] "Variable Speed Generation Subsystem Using the Doubly-fed Machine", Proposal submitted under RAA-3-12272, "Advanced Wind Turbine Next Generation Innovative Subsystems Project", National Renewable Energy Laboratory (NREL), Dallas A. Marckx (EPC Inc.), April 1993
- [5] "Propagation and Elimination of Torque Ripple in a Wind Energy Conversion System", IEEE Transactions on Energy Conversion, Vol. EC-1, No. 2, June 1986; L. Dessaint, H. Nakra and D. Mukhedkar

APPENDIX A

FIGURE A.1: VSWG SYSTEM

NOTES:

NOTE 1: EARTH GROUND IS TO BE 1 AWG INSULATED WIRE AND ISOLATED FROM ALL OTHER GROUNDING SYSTEMS.

VSG WIND PROJECT

EPC Inc.		
Corvallis, Oregon, USA		
Title		
275KW VSG POWER SYSTEM SCHEMATIC		
Size	Document Number	REV
B	FIGURE A.1	A
Date: September 22, 1993		Sheet 1 of 1

DESIGNED BY: BZ & CW
DRAWN BY: MZ

FIGURE A.2: AWT-26 CONTROLLER POWER SECTION (PARTIAL)

NOTES:

- SC1: 3 x 1.0uF, 600VAC
- LA1: Secondary Arrester
- GFR: Ground Fault Relay
- LP1: Line Protection Relay
- K_{GFR}: Relay, SPDT, 120VAC Coil
- K_{LP1}: Relay, SPDT, 120VAC Coil

DESIGNED BY: IR/RLA
CW/EPC (NEW)
DRAWN BY: MZ

EPC Inc.
1895, NW 9th Street, Suite A
Corvallis, OR 97330

Size Document Number
B A
Date: October 4, 1993 Sheet 1 of 1

FIGURE A.3: VSWG CONTROL SCHEMATIC

VSWG/AWT-26 CONTROLLER INTERFACE

EPC Inc. 1895, NW 9th Street, Suite A Corvallis, OR 97330		
Title VSWG-AWT-26 CONTROLLER INTERFACE		
Size B	Document Number FIGURE A.3	REV A
Date September 22, 1993	Sheet 5 of 6	

DESIGNED BY: CH
DRAWN BY: M2

FIGURE A.4: VSWG SYSTEM: SYNCHRONIZING DETECTOR PCB

EPC Inc.

1895 NW 9th Street, Suite A
Corvallis, OR. 97330

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26489100

Fig. 4.4

1645 1881 1881 1881

```

      .COT  "0.  31 0-31)  IN'S  31 23) 35073  : NO1110NO3  : 1 3111111
      .COT  "0.  31 0-31)  IN'S  31 23) 35073  : NO1110NO3  : 1 3111111

```

[illegible]

1. Principles of Management

- 37 -

EPC Inc. 1895, NW 9th Street, Suite A Corvallis, OR 97330		
Title		
CONTROL POWER DISTRIBUTION		
Size	Document Number	REV
B	FIGURE A.5	A
Date: September 25, 1983 Sheet 2 of 2		

FIGURE A.6: VSWG CONTROL SCHEMATIC BREAKER AND CONTACTOR LOGIC

- 38 -

DESIGNED BY: CW
DRAWN BY: MZ

EPC Inc. 1895, NW 9th Street, Suite A Corvallis, OR 97330		
Title BREAKER AND CONTACTOR LOGIC		
Size	Document Number	REV
B	FIGURE A.6	A
Date	September 28, 1993	Sheet 3 of 6

FIGURE A.7: VSWG CONTROL SCHEMATIC RELAY LOGIC

- 39 -

DESIGNED BY: CM
DRAWN BY: HZ

EPC Inc. 1895, NW 9th Street, Suite A Corvallis, OR 97330	
Title RELAY LOGIC	
Size B	Document Number FIGURE A.7
Date: September 29, 1993	Sheet 6 of 6

Figure A.10: P/Q-Measurement Board
Active and Reactive Power Measurements

Figure A.11: P/Q-Measurement Board
Low Pass Filter and V-to-I Conversion

SPECIFIC BOARD DATA	
TYPE	LOW PASS FILTER AND V TO I CONVERSION
SYMBOLIC NUMBER	110/100.000
C	110/100.000
DATE	11/10/11 11:11:11

VSWG SUPERVISORY BOARD

MAIN WORKSHEET

Figure A.12

Electronic Power Conditioning Inc. 1895, NW 9th Street Corvallis, OR 97330			
Title VSWG SUPERVISOR BOARD			
Size Document Number			
B	NREL.SCH		PK7 A
Date	October 19, 1993	Sheet	1 of 19

POWER SUPPLY

Figure A.13

Electronic Power Conditioning Inc.		
1895, NW 9th Street		
Corvallis, OR 97330		
Title		
POWER SUPPLY		
Size Document Number		
REV		
Date: September 11, 1977		

MEMORY

EPROM

RAM

SHORT 1&2 FOR 27128,27513,27011 (16K,64K,256K)
SHORT 2&3 FOR 27256 (32K)

SHORT 2 & 3 FOR 2K RAM
SHORT 1 & 2 FOR 8K RAM

Figure A.14

Electronic Power Conditioning Inc. 1895, NW 9th Street Corvallis, OR 97330		
Title	MEMORY	
Size	Document Number	REV
8		A
Date:	September 11, 1993	Sheet 3 of 15

KEYBOARD / APPLICATION INTERFACE

Figure A.15

Electronic Power Conditioning Inc. 1895, NW 9th Street Corvallis, OR 97330		
Title KEYBOARD / APPLICATION INTERFACE		
Size Document Number		
REV A		
Date: September 11, 1993 Sheet 4 of 15		

MICRO CONTROLLER

Figure A.16

Electronic Power Conditioning Inc.		
1895, NW 9th Street		
Corvallis, OR 97330		
Title	MICRO CONTROLLER	
Size	Document Number	REV
B	196DEC.5CH	A
Date:	October 19, 1993	Sheet 5 of 15

WAIT STATE GENERATOR

Figure A.17

Electronic Power Conditioning Inc. 1895, NW 9th Street Corvallis, OR 97330		
Title WAIT STATE GENERATOR		
Size B	Document Number	REV A
Date: September 11, 1993 Sheet 10 of 13

For reducing noise on the micro controller board

Figure A.18

Electronic Power Conditioning Inc. 1895, NW 9th Street Corvallis, OR 97330			
Title DECOUPLING CAPACITORS			
Size B	Document Number CAP.SCH		REV A
Date:	October 19, 1993 Sheet 9 of 15		

ADDRESS LATCH & DECODE / DATA LATCH

Figure A.19

Electronic Power Conditioning Inc. 1895, NW 9th Street Corvallis, OR 97330		
Title ADDRESS LATCH & DECODE / DATA LATCH		
Size B	Document Number	REV A
Date: September 11, 1993 Sheet 8 of 15		

SERIAL PORT

THIS BOARD IS CONFIGURED AS A DATA EQUIPMENT DEVICE.
 IT CAN BE DIRECTLY HOOKED UP TO A COMPUTER (PC).
 THE PC IS A DATA TERMINAL DEVICE
 A NINE PIN STRAIGHT RIBBON CABLE CAN BE USED

Figure A.20

Electronic Power Conditioning Inc. 1895, NW 9th Street Corvallis, OR 97330		
Title SERIAL PORT		
Size	Document Number	REV
B		A
Date	September 11, 1993	Sheet 7 of 15

Figure A.21

Electronic Power Conditioning Inc. 1095, NW 9th Street Corvallis, OR 97330		
Title RESET CIRCUIT		
Size Document Number B		REV A
Date: October 1, 1993 Sheet 6 of 11		

EXTERNAL INPUT OUTPUT DECODE

ADDRESS DECODER

ANALOG OUTPUT

ANALOG INPUT

DIGITAL INPUT

DIGITAL OUTPUT

Figure A.22

Electronic Power Conditioning Inc. 1895, NW 9th Street Corvallis, OR 97330		
Title External Input Output Decode		
Size Document Number B 108.SCH		REV A
Date: October 21, 1993 Sheet 11 of 11

Figure A.23

~~ANA OUTCO..73~~ > ~~ANA OUTCO..73~~

Electronic Power Conditioning Inc.
1895, NW 9th Street
Corvallis, OR 97330

ANALOG OUTPUTS

Size document Number

Doc	Docment Name	Rev
B		A
Date: September 11, 1993 Sheet 13 of 13		

ANALOG INPUTS

'PS' and 'CA' are to be set for some models input

0-201 0-011	1 -) OPEN	0 -) CLASH
0-1-0 0-011	1 -) CLASH	0 -) OPEN
0-1-0 0-011	1 -) CLASH	0 -) OPEN

```
'PS' IS SET AND 'CL' IS RESET FOR SV INPUT
IF BOTH 'PS' AND 'CL' ARE NOT SET THEN IT IS A LOW AND/OR INPUT
```

Figure A.24

Electronic Power Conditioning Inc.
1098, NW 9th Street
Fort Lauderdale, FL 33304

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DATE 06-07-2001 BY SP-6 BTJ/KJS

DIGITAL OUTPUTS

Figure A.25

STRENGTHENED POWER CONNECTIONS INC.	
1000, NW 25th ST	
GAINESVILLE, FL 32609	
FIGURE	DIGITAL OUTPUTS
STRENGTHENED POWER	
REV	1

DIGITAL INPUT

Optoisolator Inputs

CONTACTOR INPUTS

Variable Speed Wind Generation

Figure A.27

Runtime Control

VSG Operation Under Varying Wind Conditions

Figure A.29

**Shut - Down
Normal
(From AWT - 26 Controller)**

Ramp down ir,ref to zero
Open CB2
Confirm CB2 is open
Open Sr
Deploy blade tip brakes
(Signal to AWT - 26 Controller)

**Shut - Down
Emergency
(From AWT - 26 or VSWG controller)**

Ramp down ir,ref to zero
Trip CB2
Confirm CB2 is open
Open Sr
Deploy blade tip brakes
(Signal to AWT - 26 Controller)
Open CB2

Figure A.31

Fig. A.33

Note:
Interrupts occur every ten milliseconds.
They can occur at any time, except when
the controller is executing critical code.
What is termed critical is to be determined later.
After executing an interrupt the controller will
return to the code it was executing when the
interrupt occurred.

Figure A.33

Figure A.34

Figure A.35

Failure Modes

Fig. A.37

USRC Failure

Fig. A.38

Utility Grid Failure

Fig. A.37

USRC &
Utility Grid Failure

Trip CB1

USRC Failure

VSWG Controller failure

System Reset Mode

Fig. A.30

DFM overtemperature

Shut - Down
Normal

Fig. A.31

DFM loss of Synchronism

Shut - down
Emergency

Fig. A.37

USRC Failure

Transmission Line
Over / Under voltage

Over

Very Low

Under

Fig. A.38

Utility Grid Failure

Fig. A.31

Shut - down
Emergency

Utility Grid Failure

Defined as exceeding $\pm 10\%$ Normal utility voltage tolerance limits

Includes:

Voltage and Phase Imbalances

Phase to phase faults (Single & Three Phase)

Phase to ground faults (Single & Three phase)

Over & Under voltage

Over & Under frequency

Note:

For Multiple reclosure of breaker

System shutdown till :

Grid voltage steady for period $> 2-3$ times reclosing interval of breaker
and Period $>$ Time for cooling of mechanical brake

Figure A.39: GLOSSARY OF SYSTEM STATUS/OPERATION

Hardware - USRC, Turbine and Brake:

OFF:	Electrically blocked from operation
START:	Electrically enabled to operate
ON:	Operating within normal conditions
STOP:	Electrically disabled, shutting down
LOCKED:	OFF, requiring manual reset to restart
AVAILABLE:	OFF, no additional action (i.e., manual reset) required to restart
MALF:	Operating outside normal operating conditions, shut-down imminent

Hardware - Utility grid:

AVAILABLE:	Connected to the system (and USRC), within voltage and frequency tolerance limits, supplying power to the system controllers
CONNECTED:	The complete VSWG system (including the stator of the DFM) are connected to the grid
DISCONN:	The complete VSWG system is disconnected from the grid, CB1 either tripped or open (critical parts of the controller powered by the UPS)
MALF:	Grid outside voltage and/or frequency tolerance limits, or excessive ground-current has been detected; either the line-protection relay or the ground-fault relay will send an alarm and latch, trip of CB1 imminent

Contactors/Circuit Breakers:

CLOSE:	The device is transitioning from OPEN (source disconnected from load) to CLOSED (source connected to load)
CLOSED:	The device has connected the source to the load
OPENIN:	The device is transitioning from CLOSED (source connected to load) to OPEN (source disconnected from load)
OPEN:	The device has disconnected the source from the load
TRIP:	The breaker has automatically (or through shunt-trip) disconnected the source from the load and requires (manual) reset to OPEN

Controllers:

OFF:	The controller is electrically/manually de-activated
START:	The controller is electrically/manually activated and starts up the VSWG system
ON:	The controller executes its run-time routines
STOP:	The controller is being interrupted in its run-time routine and transitions to a controlled system shut-down
MALF:	The controller got hung up in its run-time routine, its internal watch-dog timer recognized the problem and reset the controller, resulting in a controller re-initialization which brings it back into the OFF-mode

Protective Relays:

OK:	The grid voltage/frequency is within its tolerance limits, and there are no excessive ground-currents
ALARM:	An out-of-tolerance condition has been detected and an appropriate contact closed, indicating the condition to the controllers and prompting the appropriate sequence of action
LATCHED:	Following the detection of an out-of-tolerance or fault condition, the device remains in the fault-indicating state until being reset in an appropriate manner (manually/electrically) before returning into the OK state.

VSWG STATUS/OPERATION

CASE: DFM designs 4-pole (II) and 6-pole

MODE: Normal start-up

1. INITIAL STATUS/CONFIGURATION:

Turbine off-line, but available

HARDWARE				CONTACTORS/ CIRCUIT BREAKERS				CONTROLLERS		PROTECTIVE RELAYS	
USRC	AWT-26		UTILITY GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	TURBINE	BRAKE									
OFF	AVAILABLE	ON	AVAILABLE	OPEN		CLOSED	OPEN	OFF	OFF	OK	OK

Wind sensors indicate turbines could operate: transmission grid is available

2. CHANGE-INITIATING COMMAND/CONDITION:

Start turbine (soft start)

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
START	START	OFF		CLOSE				START	START		

Establish synchronization condition across CB2 with rotor current (amplitude and frequency)

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
ON			CONNECTED	CLOSED			CLOSE	ON	ON		

Activate Q-controller and increase rpm (decrease f_r) to RPM_{target}

3. DESIRED/ACHIEVED FINAL STATUS/CONFIGURATION:

Turbine on-line

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
ON	ON	OFF	CONNECTED	CLOSED		CLOSED	CLOSED	ON	ON	OK	OK

Figure A.40

VSWG STATUS/OPERATION

CASE: DFM designs 4-pole (II) and 6-pole

MODE: Normal shut-down

1. INITIAL STATUS/CONFIGURATION:

Turbine on-line

HARDWARE				CONTACTORS/ CIRCUIT BREAKERS				CONTROLLERS		PROTECTIVE RELAYS	
USRC	AWT-26		UTILITY GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	TURBINE	BRAKE									
ON	ON	OFF	CONNECTED	CLOSED		CLOSED	CLOSED	ON	ON	OK	OK

2. CHANGE-INITIATING COMMAND/CONDITION:

Stop turbine

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
STOP			AVAILABLE				OPENIN				

Shut-down USRC, then open CB2 (wait for CB2-open confirmation before proceeding)

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
OFF	STOP			OPENIN			OPEN	STOP	STOP		

Instruct AWT-26 controller to deploy blade-tip brakes

3. DESIRED/ACHIEVED FINAL STATUS/CONFIGURATION:

Turbine off-line, but available

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
OFF	AVAILABLE	ON	AVAILABLE	OPEN		CLOSED	OPEN	OFF	OFF	OK	OK

Figure A.41

VSWG STATUS/OPERATION

CASE: DFM designs 4-pole (II) and 6-pole

MODE: Emergency shut-down (Not grid-prompted)

(Emergency Stop button activated, to include failures/malfunction of the turbine or the AWT-26 controller)

Turbine on-line

1. INITIAL STATUS/CONFIGURATION:

HARDWARE				CONTACTORS/ CIRCUIT BREAKERS				CONTROLLERS		PROTECTIVE RELAYS	
USRC	AWT-26		UTILITY GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	TURBINE	BRAKE									
ON	ON	OFF	CONNECTED	CLOSED		CLOSED	CLOSED	ON	ON	OK	OK

2. CHANGE-INITIATING COMMAND/CONDITION:

External Emergency Stop activated

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
STOP	STOP		AVAILABLE				TRIP				

Shut-down USRC first, then open CB2 (wait for CB2-open confirmation before proceeding)

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
OFF	LOCKED			OPENIN			OPENIN	STOP	STOP		

Instruct AWT-26 controller to deploy blade-tip brakes

3. DESIRED/ACHIEVED FINAL STATUS/CONFIGURATION:

Turbine off-line and locked out

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
OFF	LOCKED	ON	AVAILABLE	OPEN		CLOSED	OPEN	OFF	OFF	OK	OK

Figure A.42

VSWG STATUS/OPERATION

CASE: All DFM designs

MODE: USRC failure in DFM-mode

1. INITIAL STATUS/CONFIGURATION:

Turbine on-line

HARDWARE				CONTACTORS/ CIRCUIT BREAKERS				CONTROLLERS		PROTECTIVE RELAYS	
USRC	AWT-26		UTILITY GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	TURBINE	BRAKE									
ON	ON	OFF	CONNECTED	CLOSED		CLOSED	CLOSED	ON	ON	OK	OK

2. CHANGE-INITIATING COMMAND/CONDITION:

USRC failure detected

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
MALF				OPENIN			TRIP	STOP	STOP		

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	STOP		AVAILABLE	OPEN			OPENIN	OFF	OFF		

After confirmation that CB2 is open instruct AWT-26 controller to deploy blade-tip brakes

3. DESIRED/ACHIEVED FINAL STATUS/CONFIGURATION:

Turbine off-line

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
MALF	OFF	ON	AVAILABLE	OPEN		CLOSED	OPEN	OFF	OFF	OK	OK

Figure A.43

VSWG STATUS/OPERATION

CASE: All DFM designs

MODE: USRC and utility grid failure

1. INITIAL STATUS/CONFIGURATION:

Turbine on-line

HARDWARE				CONTACTORS/ CIRCUIT BREAKERS				CONTROLLERS		PROTECTIVE RELAYS	
USRC	AWT-26		UTILITY GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	TURBINE	BRAKE									
ON	ON	OFF	CONNECTED	CLOSED		CLOSED	CLOSED	ON	ON	OK	OK

2. CHANGE-INITIATING COMMAND/CONDITION:

USRC failure detected

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
MALF	STOP		AVAILABLE	OPENIN			TRIP	STOP	STOP	OK	OK

Utility grid failure detected

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	OFF		MALF	OPEN		TRIP	OPENIN	OFF	OFF	EITHER ONE OR BOTH LATCHED	

Instruct AWT-26 controller to deploy blade-tip brakes

3. DESIRED/ACHIEVED FINAL STATUS/CONFIGURATION:

Turbine off-line and isolated from utility grid

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
MALF	OFF	ON	DISCONN	OPEN		TRIP	OPEN	OFF	OFF	EITHER ONE OR BOTH LATCHED	

Figure A.44

VSWG STATUS/OPERATION

CASE: All DFM designs

MODE: VSWG controller failure during operation

1. INITIAL STATUS/CONFIGURATION:

Turbine on-line

HARDWARE				CONTACTORS/ CIRCUIT BREAKERS				CONTROLLERS		PROTECTIVE RELAYS	
USRC	AWT-26		UTILITY GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	TURBINE	BRAKE									
ON	ON	OFF	CONNECTED	CLOSED		CLOSED	CLOSED	ON	ON	OK	OK

2. CHANGE-INITIATING COMMAND/CONDITION:

VSWG controller failure

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
STOP			AVAILABLE	OPENIN			OPENIN	STOP	MALF		

VSWG controller resets itself, AWT-26 controller automatically instructed to deploy blade-tip brakes

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
		ON		OPEN			OPEN	OFF	OFF		

3. DESIRED/ACHIEVED FINAL STATUS/CONFIGURATION:

Turbine off-line, but available

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
OFF	OFF	ON	AVAILABLE	OPEN		CLOSED	OPEN	OFF	OFF	OK	OK

Figure A.45

VSWG STATUS/OPERATION

CASE: All DFM designs

MODE: DFM over-temperature shut-down

1. INITIAL STATUS/CONFIGURATION:

Turbine on-line

HARDWARE				CONTACTORS/ CIRCUIT BREAKERS				CONTROLLERS		PROTECTIVE RELAYS	
USRC	AWT-26		UTILITY GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	TURBINE	BRAKE									
ON	ON	OFF	CONNECTED	CLOSED		CLOSED	CLOSED	ON	ON	OK	OK

2. CHANGE-INITIATING COMMAND/CONDITION:

DFM over-temperature detected

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
STOP							OPENIN				

Shut-down USRC, open CB2 (wait for CB2-open confirmation before proceeding)

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	STOP		AVAILABLE	OPENIN			OPEN	STOP	STOP		

Instruct AWT-26 controller to deploy blade-tip brakes

3. DESIRED/ACHIEVED FINAL STATUS/CONFIGURATION:

Turbine off-line, available after DFM has cooled down

USRC	TURBINE	BRAKE	GRID	S _R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
OFF	OFF	ON	AVAILABLE	OPEN		CLOSED	OPEN	OFF	OFF	OK	OK

Figure A.46

VSWG STATUS/OPERATION

CASE: All DFM designs

MODE: Loss of DFM-Synchronism

1. INITIAL STATUS/CONFIGURATION:

Turbine on-line

HARDWARE				CONTACTORS/ CIRCUIT BREAKERS				CONTROLLERS		PROTECTIVE RELAYS	
USRC	AWT-26		UTILITY GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	TURBINE	BRAKE									
ON	ON	OFF	CONNECTED	CLOSED		CLOSED	CLOSED	ON	ON	OK	OK

2. CHANGE-INITIATING COMMAND/CONDITION:

Loss of DFM-synchronism detected

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
STOP							TRIP				

Shut-down USRC, open CB2 (wait for CB2-open confirmation before proceeding)

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
OFF	STOP		AVAILABLE	OPENIN			OPENIN	STOP	STOP		

Instruct AWT-26 controller to deploy blade-tip brakes

3. DESIRED/ACHIEVED FINAL STATUS/CONFIGURATION:

Turbine off-line, but available

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
OFF	OFF	ON	AVAILABLE	OPEN		CLOSED	OPEN	OFF	OFF	OK	OK

Figure A.47

VSWG STATUS/OPERATION

CASE: All DFM designs

MODE: Transmission line Over-/Under-Voltage
and/or Over-/Under-Frequency

1. INITIAL STATUS/CONFIGURATION:

Turbine on-line

HARDWARE				CONTACTORS/ CIRCUIT BREAKERS				CONTROLLERS		PROTECTIVE RELAYS	
USRC	AWT-26		UTILITY GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
	TURBINE	BRAKE									
ON	ON	OFF	CONNECTED	CLOSED		CLOSED	CLOSED	ON	ON	OK	OK

2. CHANGE-INITIATING COMMAND/CONDITION:

Transmission line Over-/Under-Voltage

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
STOP			MALF				OPENIN			ALARM	

Shut-down USRC, open CB2 (wait for CB2-open confirmation before proceeding)

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
OFF	STOP		DISCONN	OPENIN		TRIP	OPEN	STOP	STOP	LATCHED	

Instruct AWT-26 controller to deploy blade-tip brakes

3. DESIRED/ACHIEVED FINAL STATUS/CONFIGURATION:

Turbine off-line and isolated from utility grid

USRC	TURBINE	BRAKE	GRID	S_R		CB1	CB2	AWT-26	VSWG	LINE-PROTECT	GND-FAULT
OFF	OFF	ON	DISCONN	OPEN		TRIP	OPEN	OFF	OFF	LATCHED	OK

Figure A.48

END

DATE

FILMED

4/5/94