PNL-10667
LA Schienbein

**R. Lynette & Associates and Pacific Northwest Laboratory
Staff Exchange: Analysis and Evaluation of the Application of the Pulse
Amplitude Synthesis and Control (PASC) Converter in a Wind Power Plant**

Background

The main objective of staff exchanges is to facilitate cooperative activities between PNL staff and U.S. private industry. Funding for the projects is provided by the DOE Office of Energy Research Laboratory Technology Transfer Program.

Dr. Matthew Donnelly, a Research Engineer in the Applied Physics Center, initiated a PNL disclosure for Pulse Amplitude Synthesis and Control (PASC) converter intellectual property protection in 1993. PASC converter research at the Pacific Northwest Laboratory (PNL) has been funded through the ETDI LDRD program. Recent work has centered on building the three-phase 20kW laboratory unit, the development of control algorithms and the study of the application of PASC converters in a 25MW wind power plant (through the staff exchange with RLA reported here). An overview and description of the PASC converter is included as Appendix A.

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Purpose and Objectives

The main purposes of the project were:

- to benefit the non-Federal partner, R. Lynette & Associates (RLA) and its subsidiary Advanced Wind Turbines, Inc. (AWT)
- to identify and detail potential areas for subsequent collaborative activities
- to apply unique Pacific Northwest Laboratory (PNL) capabilities as an important step in developing future programmatically funded activities
- to analyze and evaluate the application of PNL's Pulse Amplitude Synthesis and Control (PASC) system in a wind power plant (approximately 25MW capacity, 91 275kW turbines) to be installed near Goldendale, Washington in 1995.

Specific objectives were:

- to quantify the main design and manufacturing problems that must be solved in order to bring PASC technology from its current research status to commercial use in electrical power plants
- to quantify the estimated manufacturing and installation costs of the PASC system
- to quantify the operational and cost benefits that may result from implementation of PASC

Summary of Activities Performed

The staff exchange program between PNL and RLA began in March 1994. The exchange of Dr. Lawrence Schienbein occurred during six weeks interspersed from March 21 to July 12, 1994.

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During the program, Dr. Schienbein met with RLA and AWT technical, management and administrative personnel to gather the necessary baseline wind power plant information, to discuss the details of the electrical layout and to fully understand the electrical and control system for the AWT-26 turbine. Dr. Schienbein and Dr. Matt Donnelly of PNL also met with Bonneville Power Administration (BPA) personnel to discuss the interconnection of the wind power plant with BPA's transmission system and the details of the BPA transmission system in the Goldendale, Washington area. Discussions were also held at RLA's offices with a technical representative of Cutler-Hammer in connection with the turbine control system. Dr. Schienbein organized three special meetings at the RLA offices.

- Dr. Matt Donnelly of PNL's Power Systems Group presented a technical overview of PASC to RLA and AWT engineering personnel. This was followed by in depth discussions with electrical engineering and test engineering personnel.
- Dr. Russ Westphal of Washington State University (working with Dr. Schienbein through an AWU fellowship) and Dr. Schienbein met with RLA research and engineering personnel on technology development issues pertaining to turbine wake effects, aerodynamic noise mitigation, vortex generators and aerobrakes. Dr. Schienbein followed-up with a scope statement for experimental work (using a vehicle mounted wind tunnel) to investigate the near wake of the tower and means to mitigate the wake effects. Dr. Schienbein also provided a number of technical reports and papers to Mr. Shawn Lawlor of RLA, in response to discussions on theoretical and experimental investigations of aerobrakes.
- Mr. Joon Kim (working for Dr. Schienbein through an AWU student fellowship at PNL) demonstrated the progress on and the basis for the PASC wind power plant performance and cost simulation model to RLA and AWT staff. Mr. Kim worked with Dr. Schienbein to develop the performance and cost computational model which permitted the baseline wind power plant case and the PASC cases to be analyzed. The model uses a commercial spreadsheet program.

Dr. Schienbein also met with Mr. Bill Archibald, the Executive Vice President of FloWind Corporation, at the RLA offices during the staff exchange and later at FloWind's offices (FloWind is the developer of the 25 MW Goldendale wind power plant). Dr. Schienbein and Dr. Hammerstrom of PNL (PASC converter lead technical staff member) visited the AWT-26 prototype turbine test site and met with the operations and test engineers in Tehachapi, CA on October 4, 1994, following meetings with FloWind Corporation engineering and marketing personnel on October 3, 1994.

Significant Accomplishments

Dr. Schienbein achieved all of the purposes and objectives of this staff exchange. In particular, this staff exchange has demonstrated that, through direct on-site work with private industry, good opportunities will be identified for collaboration in unanticipated areas and with other organizations. Small but strategic investments in short-term staff exchanges, such as this one, can earn a large and diverse payback.

During the staff exchange, the application of PNL's Pulse Amplitude Synthesis and Control (PASC) converter system in the 25MW Goldendale, WA wind power plant was analyzed and evaluated through conceptual design studies. A computer model was developed and used to calculate the wind power plant performance and cost. RLA and AWT engineering staff, PNL staff, BPA and Benton

PUD engineering staff provided cost, performance and technical data and expert support in quantifying the configurations, the main design and manufacturing issues, and the projected cost of the PASC converter and the wind power plant for the various configurations analyzed. The estimated manufacturing and installation costs of the PASC system were quantified along with the operational and overall wind power plant cost and energy output benefits that could result from implementation of PASC. (Selected schematics of the power plant configurations and input data are shown in Appendix B.)

The work done during the staff exchange did identify the key problems that must be solved in order to bring PASC technology from its current research status to effective use in electrical power plants. This outcome has formed the basis for planning the full-scale collaborative test and evaluation work described below.

The staff exchange of Dr. Schienbein promoted significant interaction between industry and DOE. Two firms (Zond Systems, Inc. and FloWind Corporation) have offered to work in collaboration with PNL to continue the development of the PASC converter. A third firm (Howard Industries, a transformer manufacturer) seeks to meet with PNL to discuss product development and the possible transfer of related automated manufacturing technology.

Dr. Schienbein contacted numerous companies and public sector organizations during the period of the staff exchange to brief them on the PASC converter and to ascertain their interest in participating in its development and commercialization. These included wind turbine manufacturers, wind power developers, generator and transformer manufacturers, National Laboratories and others. As a result of these contacts, two other potential collaborators in the public sector were identified for a test and evaluation program.

Significant Problems

No problems occurred during the staff exchange. RLA management and staff freely provided information and engaged in discussions. Dr. Schienbein was provided with first class office space and a personal computer. All office services and secretarial support, technical data, drawings, specifications and the library were freely accessible. Some of the necessary information was more difficult to find due to the way in which it was filed. This was a very minor problem.

Follow-on Work Accomplished

During the course of the staff exchange, FloWind Corporation acquired controlling interest in Advanced Wind Turbines, Inc. (AWT), the subsidiary of RLA developing the AWT-26 turbine. This proved to be highly beneficial because FloWind is also the wind power plant developer. Dr. Schienbein discussed the PASC work with Mr. Bill Archibald (Executive Vice President of FloWind) during a meeting at the RLA offices. In September, FloWind invited Dr. Schienbein to meet with FloWind's management, engineering and marketing personnel at FloWind's headquarters in San Rafael, CA and to visit the FloWind wind power plant at Tehachapi. At the San Rafael meeting, FloWind's controlling investor (Mr. Leon Richartz) advised Dr. Schienbein and Dr. Donnelly that FloWind was interested in pursuing a collaborative agreement with PNL to carry out a full-scale test and evaluation of the PASC converter at an existing FloWind windfarm.

In addition, Dr. Schienbein was advised that FloWind wanted PNL to carry out full-scale wake measurements of its EHD 300kW vertical axis wind turbine rotor. Dr. Schienbein followed-up with PNL's Boundary Layer Meteorology Group and Dr. Robert Thresher of the National Renewable Energy Laboratory (NREL).

The scope and preliminary results of the staff exchange at RLA triggered the interest of Zond Systems Inc. (a major fully-integrated U.S. wind power company) in collaborating on a full-scale field test and evaluation. Dr. Schienbein and Dr. Hammerstrom met with Zond Systems on October 5, 1994. Zond followed-up with a letter of intent (see Appendix C), outlining a cost-shared test and evaluation program (300kVA and involving four 65kW turbines). A Quick Response Staff Exchange/CRADA white paper was submitted (see Appendix D) and Dr. Schienbein spoke with Dr. Thresher, the director of the National Renewable Energy Laboratory's (NREL) Wind Energy Program, to solicit his interest and some DOE Wind Energy Program funding.

Recommended Further Follow-On Work

It is recommended that the CRADA with Zond Systems be aggressively pursued as Zond is highly capable, committed to the work and fully prepared to manufacture, install and test a full-scale prototype unit. A full-scale test and evaluation using four 65kW wind turbines operating asynchronously is envisioned. This configuration is an excellent vehicle to accelerate the commercialization of the PASC converter. The U.S. wind power industry could be a major user of PASC systems. If successful, this technology will allow asynchronous operation of groupings of wind turbines (and other types of generators such as diesel generator sets and solar thermal electric generators), supply reactive power to the utility grid, and electrically isolate generators for maintenance and control purposes. All three of these outcomes are of great interest to the distributed power industry where numerous generators and storage devices must be interconnected. The rate of wind power plant installation alone is currently about 1000MW per year, and is increasing. PASC converter units could replace (and enhance the function of) the conventional step up transformers currently used in this application. The cost of these transformers for 1000MW of installed capacity is about \$12.5 million, representing a potential PASC converter market of at least \$125,000,000 over the next 10 years.

It is recommended that discussions continue with FloWind regarding a potential CRADA to test and evaluate the PASC converter. A contract from FloWind to PNL to assist in measuring and evaluating the wake and wake effects of FloWind's EHD rotor should be aggressively pursued.

Dr. Schienbein has made a solid contact with Howard Industries (Laurel, Mississippi), one of the largest manufacturers of distribution transformers in the U.S. Howard Industries is actively seeking technologies to broaden its product base and wishes to meet with PNL to discuss possible development and manufacturing of PASC converters and related automated manufacturing technologies. This meeting should be pursued.

Senior management at RLA expressed considerable interest in the computer model as a tool for optimizing the electrical design of wind power plants. They requested a second demonstration of the model. Dr. Schienbein requested additional PNL support to enhance and upgrade the model to improve its accuracy and to permit it to be used as an iterative design tool. It is recommended that this work be funded and completed.

Potential Benefits from Pursuing Follow-On Work

The PASC converter system could substantially reduce the cost and complexity of the wind power plant's electrical and control subsystems and provide U.S. based wind power plant developers and manufacturers with a long-term competitive edge over foreign competitors. This will permit U.S. firms to improve their competitive position in developing wind power plants both inside and outside of the U.S. with U.S. designed and manufactured wind turbines and windfarm electrical technology. PASC converter technology is also applicable to other power plants that use arrays of generators and storage devices, such as solar-thermal electric generators and fuel cells.

Full-scale test and evaluation will clearly identify the technical and cost problems associated with commercialization. Further research and development activities can then be focussed on these problems. Working directly with the user and equipment manufacturer is clearly a distinct advantage.

Appendix A

Description of the PASC Converter

The PASC Converter

For Power System Applications

- Asynchronous Generation for Watershed Management
- Consolidation Applications (Battery, Wind, Solar, MHD)
- Reactive Support for Voltage Stability
- NUG's
- No loss of inertia

I. Introduction

Battelle Pacific Northwest Laboratories (PNL) and Montana State University (MSU) are currently involved in research and development focusing on PASC (Pulse-Amplitude Synthesis and Control) converter technology. PNL's interest in PASC originated in response to discussions on the feasibility of asynchronous or variable speed generation on the Columbia River in the northwestern United States. It is postulated that the capability to generate asynchronously would add flexibility to the management options for fisheries associated with the Columbia River ecosystem. In addition to the applicability to this problem, the unique consolidation features of PASC make it an attractive option for use in conjunction with some emerging generation and storage technologies such as battery arrays, fuel cells, solar arrays, wind farms, and MHD. Non-Utility Generation (NUG's) may also benefit from the flexibility and isolation that PASC provides. In this application, the host utility is isolated from the control problems encountered by the power producer's rotating machinery while the power producer is not restricted to synchronous operation with the host utility. With this flexibility, the host utility may also find it desirable to use the NUG for reactive power support or other functions. In any of these applications, the PASC converter provides a low harmonic content ac waveform without any apparent loss of generation inertia as is the case with conventional converter technology.

II. Overview & History

One type of PASC converter is made up of several (to hundreds of) three winding transformers. Each transformer consists of two identical primaries and a single secondary. Individually, each transformer makes up one n^{th} of the entire MVA rating of the converter where n is the number of transformers comprising the system. This allows the switching components of a PASC converter to be rated at the low voltage - low power specifications of a single PASC transformer rather than the high voltage - high power

rating of the entire converter. A schematic diagram of a single phase PASC inverter is shown below. The extension to three phase is straightforward with the composite secondary winding becoming one leg of the three phase converter.

Two striking advantages of the PASC technology can be readily seen from the diagram. The first is the ability to incorporate low power solid-state devices as switches in the PASC converter. An engineer familiar with conventional converter technology may want to think of this aspect of the PASC converter as analogous to the parallel strings of valves commonly used to reduce the current in any single valve of the converter. A problem with this method of reducing current in individual valves lies in the difficulty in obtaining an equal current split between parallel strings. In the case of the PASC converter however, the electrical isolation provided by the consolidation transformers alleviates these problems. A second advantage of PASC technology as seen from the diagram is the aforementioned electrical isolation between source legs of the primaries. While isolation and consolidation is not a concern when dealing with a single dc source, it becomes a crucial concern in the case of new generation and storage technologies with distributed sources such as MHD, wind and solar, batteries, and asynchronous generation.

The PASC research originated at MSU in 1986 through a contract with the Department of Energy as a novel means of consolidating the numerous electrodes of a Faraday operated MagnetoHydroDynamic (MHD) generator and stepping up the

voltage ten-fold. This was in response to a perceived need for this technology in the Strategic Defense Initiative. A 1962 NASA Technical Note on Advanced Static Inverter technology was used as a basis for what later became the PASC converter. During the course of the contract, a working 24 kW prototype inverter was built and extensively tested. Much of the development work on the prototype went into advanced computer control algorithms that eventually made the device suitable for the power system application by cleaning up the 60 Hz sinusoid. The DOE contract expired in early 1990. Research continued on the design at MSU and was picked up in a collaborative effort at PNL in 1992.

III. Ongoing Research Efforts

In order to study the applicability of the PASC converter to the power system, models have been constructed in both PSPICE, a circuit analysis program, and ATP, a commonly used power system transients program. We are finding the PSPICE model to be useful in areas such as transformer design and switching losses while the EMTP model is used to study the interaction of the PASC inverter with the existing components of the power system — particularly synchronous machines.

One of the most interesting potential applications of PASC is in conjunction with asynchronous or variable speed generation at hydro-electric plants. Increasing environmental and regulatory constraints along heavily developed waterways such as the Columbia River dictate sometimes drastic changes in the flow rates through specified power plants. Concerns over generation efficiencies over these broad operating conditions have sparked some interest in the possibility of varying the speed of the affected turbines. Currently the turbine speed is effectively "locked-in" to the synchronous speed of 60 Hz (electrical). One scenario for asynchronous generation involves the several turbines at a given power plant to be each operating at its own calculated peak efficiency for the specified flow rate and head. The resulting electrical energy generated at various frequencies and voltages from each machine would then be rectified and sent to the PASC inverter where it would be consolidated and inverted to clean 60 Hz ac. A logical intermediate step in this scheme would be to place a storage device such as SMES where there is already dc available.

It is anticipated that this scheme would not only increase efficiency, but would lead to less stress on the mechanical components of the hydro-generator (due to less governor action), increase the flexibility of the reactive power control (the generator operates at unity power factor and the PASC inverter delivers reactive power), and provide for modulation control and smoothing of the diurnal fluctuation of electrical demand (through the storage device). The ATP model of the PASC inverter is currently being used to develop test cases to illustrate these points.

In concurrent research efforts, a digital controller is being tested on the 24 kW prototype inverter located at MSU. The controller being tested is based on a Harris single-board computer programmed in the FORTH language. The Internal Model Principle of control theory is used with feedback control to generate a low-harmonic 60 Hz sinusoid into a resistive load. A gain scheduling adaptive control algorithm that was developed using a Continuous Fourier Transform (CFT) will also be tested in the future. The theory behind the adaptive algorithm is that as switching increases, low-order harmonics decrease at the expense of increased losses and increased higher-order harmonics. The engineer chooses a cost function that penalizes all three of these weighted variables and the controller gain is adjusted so as to minimize the cost function. In simulations, the controller operating on the PASC inverter without the gain scheduling has proven to be within the new IEEE 519 harmonics standards for generation equipment without additional filtering. The

adaptive controller may simply prove to be "icing on the cake".

Finally, some potential benefits in the arena of MHD are also currently being explored. Some preliminary research indicates that the unique consolidation features of the PASC inverter may be beneficial in reducing undesirable arcing within an MHD channel. Since each MHD electrode pair can be controlled individually, PASC allows for some innovative approaches to dynamic loading and manipulation of the thermodynamics of the system.

IV. Some Potential Benefits

While active research is presently being conducted to exploit the benefits of PASC technology in a wide range of applications, Battelle's immediate interests are primarily in the area of asynchronous generation as described above. In this light, one of the primary concerns in discussions surrounding large inverters delivering power from hydro generation is loss of inertia. For example, the largest single inertia in the Pacific Northwest is the Grand Coulee complex. Since conventional inverters cannot commutate without load-side line voltage, they must follow the load-side frequency in order to operate. If one chooses the definition of inertia to be the ability of a source to resist change in velocity, then generation fed through a conventional inverter has no inertia. It would certainly be a disaster to the western United States to lose all of the inertia supplied by the Coulee generation. However using this same definition, one could argue that generation behind a PASC inverter has infinite inertia. To illustrate, one potential role for PASC is to provide the system with an exact timing reference. A timing signal may be picked up from a source like the Global Positioning System (GPS) satellite network and the PASC inverter could be instructed to use that timing signal to generate a sinusoid at precisely 60 Hz. This 60 Hz sinusoid has the capability to ride through nearly any external power system disturbance or event. Of course one would not want to let Coulee lose synchronization with the rest of the system, but the example presented illustrates that there is no loss of inertia in using a PASC inverter on the power system.

One can also see a potential benefit of PASC technology in the area of reactive support. Currently, reactive support delivered by generation is limited in the short-term by over-heating of the generator's field windings. An area of active research is the use of generator reactive support to prevent voltage collapse. In the case of a PASC inverter, reactive support will be limited by the current carrying capabilities of the solid-state switches used. The synchronous generator will simply be operating at unity power factor, oblivious that reactive power is being requested from the PASC converter. The solid-state switches will be sized with the economic benefits of reactive support in mind.

For more information:

Further information on PASC research efforts can be obtained from the Energy Sciences Department of Battelle Pacific Northwest Laboratories, Battelle Boulevard, Richland, WA, (509)375-6389.

Appendix B

Baseline Wind Power Plant and PASC Configuration Data

Wind Power Plant Layout

Typical Row Layout

PASC2 Wind Power Plant Layout

:Fuse Disconnect

:PASC system

:Turbine group

A B C D E F G H I J K L M N O P Q R S T U

Transformer and Circuit Breaker Tables					[BASELINE.XLW]TRANCOST.XLS					
Pad Mount, Oil Filled Transformers					Oil Filled Circuit Breakers			Feeder Section, Branch Circuit (240 V, 480 V, 600V)		
KVA	NLL	LL	at Cos	total Cost	Voltage,k	at Cos	total Cost	Capacity	Mat. Cos	Total Cost
150	353	1170	\$7,800	\$8,959	15	\$21,240	\$25,000	60	\$333	\$341
225	481	1,478	\$8,500	\$11,000	20	\$24,240	\$28,000	100	\$1,304	\$1,445
300	554	1,872	\$9,400	\$12,300	25	\$27,240	\$32,000	125	\$1,280	\$1,480
400	617	2,382	\$11,400	\$14,800	30	\$30,240	\$36,000	150	\$1,598	\$1,875
500	712	2,984	\$14,200	\$18,000	35	\$33,240	\$40,000	200	\$2,455	\$2,800
750	1,112	4,184	\$19,200	\$24,000	40	\$36,240	\$44,000	250	\$3,475	\$4,000
1000	1,384	5,180	\$24,200	\$30,000	45	\$39,240	\$48,000	300	\$4,475	\$5,000
1500	1,980	8,180	\$34,200	\$42,000	50	\$42,240	\$52,000	400	\$7,475	\$8,000
2000	2,573	12,180	\$44,200	\$56,000	55	\$45,240	\$56,000	500	\$9,475	\$10,000
2500	3,167	15,180	\$54,200	\$68,000	60	\$48,240	\$60,000	600	\$11,475	\$12,000
3000	3,760	18,180	\$64,200	\$80,000	65	\$51,240	\$64,000	700	\$13,475	\$14,000
3750	4,649	22,647	\$74,200	\$94,000	70	\$54,240	\$68,000	800	\$15,475	\$16,000

fuse disconnects

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3	Line Rated Line																			
4	No.	Current (A)	Avg. Line Current (A)	Length(m)	Wire Size (AWG)	R/L (ohms/mile)	Loss (kWh/year)	Cost	Wire Size (AWG)	R/L (ohms/mile)	Loss (kWh/year)	Cost								
5	1	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
6	2	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
7	3	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
8	4	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
9	5	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
10	6	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
11	7	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
12	8	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
13	9	348.2	111.9	281.9	350	1588	24,497.7	\$3,829	1/0	5285	40,612.9	\$12,316								
14	10	348.2	111.9	281.9	350	1588	29,926.4	\$4,677	1/0	5285	49,612.8	\$15,045								
15	11	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
16	12	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
17	13	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
18	14	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
19	15	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
20	16	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
21	17	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
22	18	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
23	19	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
24	20	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
25	21	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
26	22	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
27	23	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
28	24	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
29	25	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
30	26	348.2	111.9	281.9	350	1588	24,497.7	\$3,829	1/0	5285	40,612.9	\$12,316								
31	27	348.2	111.9	281.9	350	1588	29,926.4	\$4,677	1/0	5285	49,612.8	\$15,045								
32	28	348.2	111.9	281.9	350	1588	35,357.2	\$5,526	1/0	5285	58,616.1	\$17,776								
33	29	348.2	111.9	281.9	350	1588	29,926.4	\$4,677	1/0	5285	49,612.8	\$15,045								
34	30	348.2	111.9	281.9	350	1588	24,497.7	\$3,829	1/0	5285	40,612.9	\$12,316								
35	31	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
36	32	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
37	33	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
38	34	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
39	35	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
40	36	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
41	37	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
42	38	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
43	39	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
44	40	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
45	41	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
46	42	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
47	43	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
48	44	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
49	45	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
50	46	348.2	111.9	281.9	350	1588	40,789.3	\$6,375	1/0	5285	67,621.5	\$20,506								
51	47	348.2	111.9	281.9	350	1588	35,357.2	\$5,526	1/0	5285	58,616.1	\$17,776								
52	48	348.2	111.9	281.9	350	1588	29,926.4	\$4,677	1/0	5285	49,612.8	\$15,045								
53	49	348.2	111.9	281.9	350	1588	24,497.7	\$3,829	1/0	5285	40,612.9	\$12,316								
54	50	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
55	51	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
56	52	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
57	53	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
58	54	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
59	55	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
60	56	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
61	57	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
62	58	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
63	59	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
64	60	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
65	61	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
66	62	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
67	63	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
68	64	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
69	65	348.2	111.9	281.9	350	1588	24,497.7	\$3,829	1/0	5285	40,612.9	\$12,316								
70	66	348.2	111.9	281.9	350	1588	29,926.4	\$4,677	1/0	5285	49,612.8	\$15,045								
71	67	348.2	111.9	281.9	350	1588	40,789.3	\$6,375	1/0	5285	67,621.5	\$20,506								
72	68	348.2	111.9	281.9	350	1588	35,357.2	\$5,526	1/0	5285	58,616.1	\$17,776								
73	69	348.2	111.9	281.9	350	1588	29,926.4	\$4,677	1/0	5285	49,612.8	\$15,045								
74	70	348.2	111.9	281.9	350	1588	24,497.7	\$3,829	1/0	5285	40,612.9	\$12,316								
75	71	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
76	72	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
77	73	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
78	74	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
79	75	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
80	76	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
81	77	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
82	78	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
83	79	348.2	111.9	281.9	350	1588	24,497.7	\$3,829	1/0	5285	40,612.9	\$12,316								
84	80	348.2	111.9	281.9	350	1588	29,926.4	\$4,677	1/0	5285	49,612.8	\$15,045								
85	81	348.2	111.9	281.9	350	1588	35,357.2	\$5,526	1/0	5285	58,616.1	\$17,776								
86	82	348.2	111.9	281.9	350	1588	29,926.4	\$4,677	1/0	5285	49,612.8	\$15,045								
87	83	348.2	111.9	281.9	350	1588	24,497.7	\$3,829	1/0	5285	40,612.9	\$12,316								
88	84	348.2	111.9	281.9	350	1588	19,072.9	\$2,981	1/0	5285	31,619.6	\$9,589								
89	85	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
90	86	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
91	87	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
92	88	348.2	111.9	281.9	350	1588	3,038.6	\$475	1/0	5285	5,037.4	\$1,528								
93	89	348.2	111.9	281.9	350	1588	8,265.8	\$1,292	1/0	5285	13,703.2	\$4,156								
94	90	348.2	111.9	281.9	350	1588	13,656.7	\$2,134	1/0	5285	22,640.4	\$6,866								
95	91	348.2																		

Appendix C

Letter of Intent from Zond Systems Inc.

The logo for Zond Systems Inc. features the word "Zond" in a stylized, handwritten-style font. The letter "Z" is particularly large and loops around the "o". The logo is positioned above a solid black rectangular bar.

ZOND SYSTEMS INC.

October 14, 1994

Analytic Science and Engineering Department
Battelle Pacific Northwest Laboratory
P. O. Box 999, MS K5-20
Richland, WA 99352

Attention: Dr. Lawrence Schienbein
Staff Engineer

Dear Dr. Schienbein:

It was a pleasure meeting both you and Dr. Hammerstrom on October 5, 1994 and discussing the potential of the Pulse Amplitude Synthesis and Control (PASC) converter system.

We have discussed the results of that meeting and the technical information that you provided prior to the meeting. Our conclusion is that the PASC conversion technology has the potential to decrease the cost of energy delivered by large scale wind power plants and to provide network stability and power quality benefits to the power generator and to the customer. Therefore, Zond Systems wishes to carry out, in collaboration with the Pacific Northwest Laboratory (PNL), a test, evaluation and demonstration of a PASC system coupled to four of our 65kW wind turbines. We would like to begin immediately, subject to reaching agreement on a contract.

We envision a division of the work and associated costs as described on the attached preliminary proposed work breakdown. In general, we propose that PNL develop the design of a 300kVA PASC converter, including the control algorithm, that Zond would build and install. Zond and PNL would jointly develop the test and evaluation plan, and Zond would supply and install the necessary test instrumentation and the data acquisition system. Zond would lead in carrying out the test and evaluation with PNL's participation. PNL would provide letter reports in connection with its work. PNL and Zond would jointly assess and interpret the test results. In addition, PNL would extend the work with its 24kVA PASC lab bench unit to include investigations of the control and interconnection of an induction generator. This would be done in parallel with the field testing as described. Zond also anticipates that we can enter into an exclusive world-wide agreement on utilizing the new technology.

Zond Systems is U.S. owned and based, and is one of the world's leading wind power companies with 2800 utility scale wind turbines in operation in five wind power plants. Zond develops, constructs, operates, owns or manages wind power generation facilities, including its 500kW Z-40 turbine, for utilities and others. Zond's wind turbines generated 580 million kWh in 1993 with a system-wide availability exceeding 97%. The company is headquartered adjacent to one of its largest operating facilities in Tehachapi, CA.

P.O. Box 1910, 13000 Jameson Road
Tehachapi, California 93561
805/822-6835
FAX: 805/822-7880

Dr. Lawrence Schienbein
Battelle Pacific Northwest Laboratory

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We are currently planning and developing new large-scale wind power plants to be constructed world-wide. Advanced power conversion technology is one of the keys to expanding our worldwide market for wind power plants. We are already investing in the development of systems that may be instrumental in reducing the cost of energy produced and adding value to the wind power plants by enhancing the quality of power delivered to the utility customer. The PASC converter could be a key element in our advanced power conversion system architecture.

We look forward to your positive response to our proposed collaboration.

Sincerely,

Kevin Cousineau

KC:bb

**PRELIMINARY PROPOSED WORK BREAKDOWN
PASC CONVERTER SYSTEM TEST & EVALUATION COLLABORATIVE PROJECT**

Zond Systems Inc. and Pacific Northwest Laboratory

ACTIVITY	PNL	ZOND
Design the 300kVA PASC converter, including the control algorithm. Prepare the necessary schematics, specifications and a letter report	x	
Organize and lead the design review.		x
Prepare the manufacturing drawings and specifications.		x
Design iteration activities and design finalization.	x	x
Build, install and commission the PASC converter.		x
Design, construct, install and commission the controller hardware.		x
Supply and install the test instrumentation and DAS.		x
Lead the development of the test and evaluation plan.	x	
Lead and manage the test and evaluation program. Provide the necessary test engineering and technician support.		x
Participate in the testing in an advisory capacity.	x	
Carry out the data analysis and interpretation.	x	x
Extend the laboratory 10kVA bench scale testing in parallel with the field program.	x	
Prepare letter reports on relevant tasks.	x	

Appendix D

Quick Response Staff Exchange White Paper

White Paper
Personnel Exchange and Quick Response CRADA
Zond Systems, Inc. (Tehachapi, CA) and Pacific Northwest Laboratory

I. Purpose

The proposers seek funding under both the staff exchange and quick response CRADA programs.

The purpose of the project is to design, build, test and evaluate a full-scale 300kVA rated Pulse Amplitude Synthesis and Control (PASC) converter working with four 65kW wind turbine generators. Zond Systems has enthusiastically endorsed a collaborative effort in which PNL supplies design expertise and Zond Systems builds and tests the full-scale prototype.

If successful, this technology will allow asynchronous operation of groupings of wind turbines (and other types of generators such as diesel generator sets and solar thermal electric generators), supply reactive power to the utility grid, and electrically isolate generators for maintenance and control purposes. All three of these outcomes are of great interest to the distributed power industry where numerous generators and storage devices must be interconnected. The rate of wind power plant installation alone is currently about 1000MW per year, and is increasing. PASC converter units could replace (and enhance the function of) the conventional step up transformers currently used in this application. The cost of these transformers for 1000MW of installed capacity is about \$12.5 million, representing a potential PASC converter market of at least \$125,000,000 over the next 10 years. Based on discussions to date, it is expected that Zond Systems will seek a license to design, manufacture and sell PASC converter systems worldwide. Since Zond is a major developer of wind power plants, it is expected that Zond Systems will also use PASC converter units in its future wind power plant installations, including, for example, a 50MW power plant near The Dalles, Oregon (Wasco County) and a 6MW plant to be constructed for Central and South West Corporation in Texas.

II. Background

Zond Systems is a small U.S. owned and based company employing about 150 people. The company is headquartered adjacent to one of its largest operating facilities in Tehachapi, CA. It is one of the world's leading wind power companies with 2800 utility scale wind turbines in operation in five wind power plants. Zond develops, constructs, operates, owns or manages wind power generation facilities for itself, utilities and others. Zond's wind turbines generated 580 million kWh in 1993 with a system-wide availability exceeding 97%. Zond has established itself as a quality designer and builder of intelligent wind turbine control and instrumentation modules, wind turbines and rotor blades. It manufactures the 500kW rated Z-40, the largest wind turbine commercially produced in the U.S. Zond Systems is a leader in the area of wind turbine control and instrumentation systems, directed by Kevin Cousineau, Manager of Electronics Research and Development. It has the expertise to design, evaluate and construct power conditioning interfaces utilizing PASC topology.

Dr. Matthew Donnelly, a Research Engineer in the Applied Physics Center, initiated a PNL disclosure for PASC intellectual property protection in 1993. PASC converter research at PNL has been funded through the ETDI LDRD program. Recent work has centered on building the three-phase 20kW laboratory unit, the development of control algorithms and a study of the application of PASC converters in a 25MW wind power plant (through a staff exchange with R. Lynette & Associates/Advanced Wind Turbines, Inc. of Redmond, Washington).

Dr. Donnelly and Dr. Donald Hammerstrom have experience in the design and construction of PASC prototypes and will lead the design of the full-scale PASC converter. Donnelly was instrumental in building the original single phase PASC prototype at Montana State University and has since been

active in developing control algorithms. Hammerstrom has investigated several variations of the basic PASC configuration and built the three phase 20kW PNL benchtop PASC prototype. Dr. Lawrence Schienbein brings 18 years of wind turbine research, design, testing and operations experience to the PNL/Zond PASC team and will serve as principal investigator. Dr. Larry Wendell, Victor Morris and James Barnard (Boundary Layer Meteorology Group, Earth and Environmental Sciences Center) will provide consulting support in control system design and data evaluation, with special expertise in the areas of wind inflow and turbine response characterization.

III. Approach

The main tasks and assignments are shown below. In general, PNL will supply the technology and the design and engineering expertise and Zond will construct and instrument the PASC device. PNL and Zond will test the PASC converter and interpret, evaluate and document the results. PNL will also expand its testing of the 20kW bench test unit to assist in developing the control system.

Task	Task Performer	Estimated Completion
PASC Converter Design	PNL	3 months
Test and Evaluation Plan	Both (PNL Lead)	4 months
Control System Design	PNL	5 months
Design Review and Iteration	Both (Zond Lead)	6 months
Construction and Installation	Zond	15 months
Instrumentation and Data Acquisition Installation	Zond	15 months
Field Testing and Evaluation	Both (Zond Lead)	18 months
Additional testing using the 20kW lab bench unit	PNL	4 months
Documentation and Reporting	Both (PNL Lead)	As tasks are completed

IV. Resource Contributions

It is estimated that the proposed CRADA will require DOE funding of \$150,000 over a period of 18 months, with work assumed to begin in January 1995. This funding would cover the design of the hardware and software, development of the test and evaluation plan, reporting to DOE and the non-Federal partner, travel to Zond's engineering offices during the design phase and to the test site, extended experiments using the 20kW PNL lab unit in support of the full-scale application, and interpretation of the test and evaluation results. \$120,000 is requested for FY95 and \$30,000 for FY96.

We have identified the possibility of obtaining some DOE Wind Energy Program funding, based on very recent discussions with Dr. Robert Thresher, the director of the Wind Energy Program at NREL. The proposers are actively pursuing this possibility. A project funded jointly by the PNL Quick Response CRADA Program and DOE's Wind Energy Program would demonstrate cross Assistant Secretary leadership and collaboration in moving technology from inception at a National Laboratory to demonstration and commercialization, consistent with DOE's imperative.

Zond will contribute the labor and materials needed to prepare manufacturing drawings and to construct the PASC converter. This cost is estimated to be at least \$150,000. Zond will also contribute the instrumentation/DAS and technician/engineering support during testing and evaluation, estimated at \$100,000. The total value of Zond's contribution is estimated to be at least \$250,000.