State Estimation for the NEPTUNE Power System

Chen-Ching Liu, Fellow*, IEEE*, Kevin Schneider, Student Member, *IEEE*, Harold Kirkham, Senior Member, *IEEE*, Bruce Howe, Senior Member, *IEEE*

Abstract - Even operation under normal operating conditions is challenging for the NEPTUNE power delivery system, a cabled dc network with multiple distributed loads. The problem comes about because the power management system must control a system that is severely limited in the number and location of measurements. The modified state estimation approach taken to address this challenge is described.

I. Introduction

In the past, power limitations have restricted long term oceanographic studies to using only low power instrumentation. NEPTUNE seeks to relax the power constraints on oceanographic research by extending a power delivery system into the Pacific Ocean [1, 2, 3, 4].

Terrestrial power systems are based on interconnected ac networks with parallel loads, while underwater telecommunications are dc point-to-point series systems. The proposed NEPTUNE power system is different from both. It is a highly interconnected dc system with a combination of series and parallel loads. It will consist of a 3000 km cabled sub-sea network with two shore landings, intended to supply power at approximately forty-six locations, see Figure. 1.

Each of these forty-six nodes will provide a point of interconnection for scientific equipment, where both power and communications services are available.

In order to maximize the deliverable power, the system will operate at -10 kV with respect to the ocean. While the nominal -10 kV voltage is well below standard transmission system voltages, it is the maximum rated voltage for standard under-sea telecommunications cables that will allow for a 30 year life span. The voltage supplied at the science nodes for use by the science users will be 400V and 48V, via power converters.

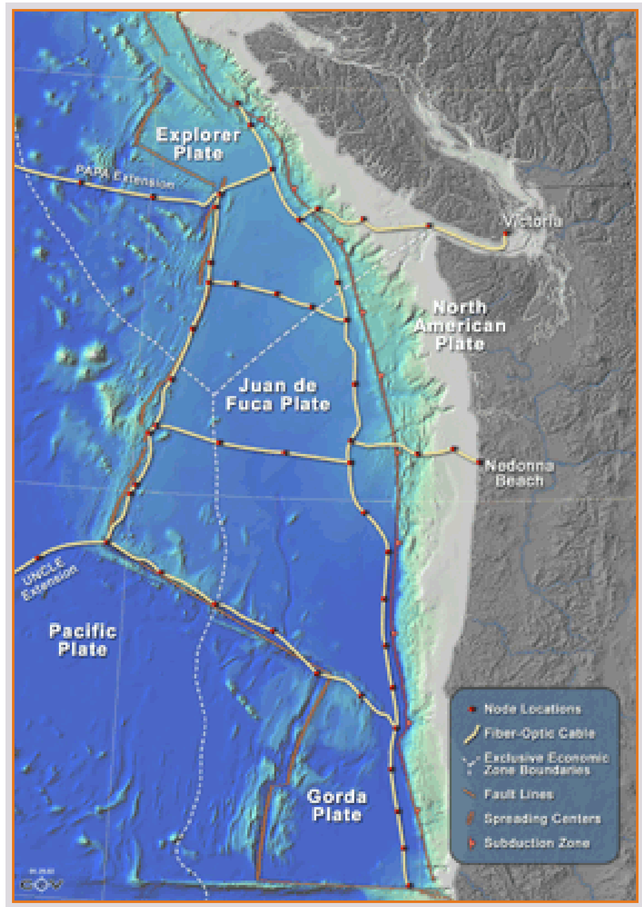

Figure 1 The proposed NEPTUNE observatory in the northeast Pacific

Power is supplied to the system from two planned shore stations, one in Oregon and the other in British Columbia. The system will use a single conductor telecommunications cable, referred to as the backbone cable, and will utilize a sea water return path.

The circuit arrangement at the node is illustrated in Figure 2. The configuration is driven largely by the issue of deployment: a cable ship is required to lay the backbone cable, and perhaps the science node, too. However, once it is laid, the science node can be retrieved by a UNOLS ship, a vessel available at low cost to the academic ocean community. The science node is therefore separated from the backbone by a spur cable of a couple of ocean depths – perhaps 8 or 10 km in some instances.

It is intended that the science load, the instruments, be served by dc/dc converters, delivering a stable 400 V from the

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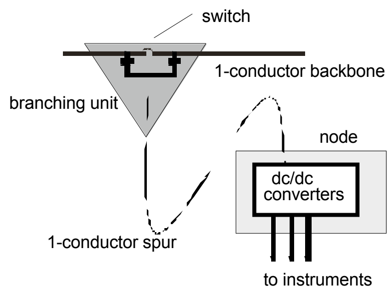

Figure 2. Circuit configuration at the science node

incoming backbone, whose voltage could droop under load to considerably below the nominal 10 kV [5]. It should be kept in mind that the cable resistance is about 1 _/km, which means that at high loads, the voltage-drop between nodes could be as much as 1 kV.

While there is certainly an adequate supply of power at the science node, our intention is to power the switch in the backbone circuit from a series-type power supply in the backbone cable. This kind of supply is not particularly efficient, as it is based on the use of a Zener diode, but is remarkably reliable. Furthermore, reliability is the key to the design of the NEPTUNE power system.

With a series power supply in the Branching Unit, and with the simplest feasible implementation for the controls, we calculate that we can design a system that has only a 50% chance of requiring a service visit to a BU in the 30-year life of NEPTUNE. However, because of the need for simplicity, there is no communication system access to the BU. Consequently, the voltage, the currents and even the state of the switch are not known to the power management system operating on shore.

For operational reasons, and unlike a conventional terrestrial power system, the NEPTUNE power system operates in four distinctly separate modes; normal, faulted, fault locating, and restoration (Figure 3). The state estimation function can only be performed in the normal and restoration modes of operation. For this reason this paper will deal primarily with the normal mode of operation.

In order to supply power to the entire system, it is planned to energize BU's, and subsequently nodes, sequentially from shore, in the restoration mode of operation. Once power is applied to the first off-shore BU a 'dummy' load is energized in order to draw the _ ampere of current through the back bone that is necessary to operate the series power source in the BU's. Once there is power available to the control processor in the BU, automated sequences determine what the present mode of operation for the system is. If the BU processor determines that the system is operating normally, the associate science node can be energized and the back bone breaker closed allowing for the system restoration to continue.

When the BU processor determines that energizing the science node is the appropriate action a breaker is closed to supply power to the science node startup circuit. After approximately 10 seconds the start-up circuits enables one of

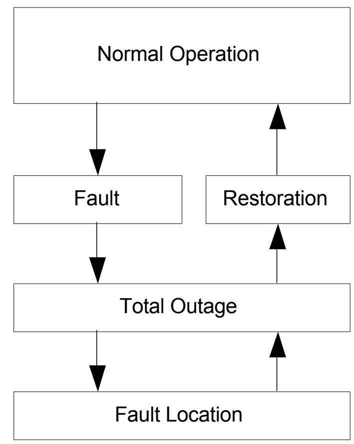

Figure 3 Four modes of the NEPTUNE power system

the main power converters in the science node to begin operation.

As soon as the science node's main power converter is operating, the communications system, based on Internet technology, begins its own start-up period. The communications start-up has a duration of between one and two minutes at each node. Once power and communications have been supplied to a node, external load can be supplied if necessary as well as shifting the operational task of ensuring _ ampere of current flow on the back to continuous duty cycle dummy loads in the science nodes. After a predetermined time the dummy loads in the BU switch off. If connection of the science loads is deferred until the entire system is connected, then the system loads will be known. This allows for the calibration of the measurement devices by comparing the measurements to a power flow calculation.

The backbone breaker is actually a complex system of several switches. When closing, a pre-insertion resistor will be used to limit the current through the breaker. This serves two purposes. First, it limits the voltage drop on the preceding cable that would be caused due to charging the capacitance of the next section. Second, it allows for the protection system to detect a cable fault before full power is applied. The full closing sequence for a backbone breaker will occupy only a few milliseconds.

By repeating this sequence, the NEPTUNE system can be completely interconnected. Since NEPTUNE is a network, it will be able to operate with multiple nodes and/or cables out of service. This feature of the power system will allow for reliable delivery of power.

The major contribution of this paper will be that it outlines a functional algorithm for state estimation in a highly interconnected direct current system with a high degree of unobservability. In addition to the unique interconnected direct current configuration, the limited number of measurements points will also addressed.

The well known issues of bad data identification [6] and errors in the system topology will also be examined and a proposed method of solving the problem proposed.

II. State Estimation

Before a system can implement a functional control scheme, the current state of the system must be known. Without knowing the state of a system, even the most complicated control system will be handicapped. State estimation is the process by which system variables are estimated using measurements made on the system in addition to known system parameters. In a conventional terrestrial power system state estimation involves the measurement of the various bus voltages and power injections, and the bus angles are the estimated quantity. Since NEPTUNE is a direct current system there are no phase angles to be concerned with. Instead, the concern is with the fact that while the voltages and currents at the science nodes can be measured, the voltages and currents at the BU's cannot be measured.

The first step in performing a state estimation is to relate the measured values to the unknown state variables [6], Equation 2.1.

$$Z^{meas} = H \cdot x^{est} \qquad (2.1)$$

The estimate can then be obtained from

$$x^{est} = H^{-1} \cdot Z^{meas} \qquad (2.2)$$

where:

Z^{meas}: The measured values of the system
H: Matrix of coefficients relating the known and unknown variable
x^{est}: The estimated value of the unknown variable

The formulation of 2.2 makes it clear that state variable can only be determined if the number of measured parameters is equal to the number of state variables. In the form of Equation 2.2 there is no ability to account for measurement errors, a powerful function of state estimation. In order to include errors in the calculations a new matrix, R, which is a diagonal matrix of variance values will be used. The next step is to construct an expression the gives the maximum likelihood of the state variables, through a least square calculation.

$$J(x) = \left(Z^{meas} - x\right)^T \left(R^{-1}\right)\left(Z^{meas} - x\right)$$
(2.3)

$$\min J(x) = \begin{bmatrix} \left(Z^{meas^T} \cdot R^{-1} \cdot Z^{meas}\right) - \\ \left(x^T \cdot H^T \cdot R^{-1} \cdot Z^{meas}\right) - \\ \left(Z^{meas} \cdot R^{-1} \cdot H \cdot x\right) + \\ \left(x^T \cdot H^T \cdot R^{-1} \cdot H \cdot x\right) \end{bmatrix}$$
(2.4)

By taking the gradient of 2.4, 2.5, it is found that

$$\nabla J(x) = -2 \cdot H^T \cdot R^{-1} \cdot Z^{meas} + 2 \cdot H^T \cdot R^{-1} \cdot H \cdot x$$
(2.5)

Solving for the estimated values of the state variables when $\nabla J(x) = 0$, one obtains

$$x^{est} = \left(H^T \cdot R^{-1} * H\right)^{-1} \cdot H^T \cdot R^{-1} \cdot Z^{meas}$$
(2.6)

Inspection of 2.6 reveals that the state variables are now estimated by a set of terms that include the errors of the measurements, diagonal elements of the R matrix. In contrast to 2.2, 2.6 generalizes to allow for the number of measurements to exceed the number of unknown state variables. When the number of measurements exceeds the number of unknown state variables, the error of an individual measurement has less effect on the overall state estimation. This is the general method that will be used as the state estimation module of NEPTUNE's Power Monitoring And Control System (PMACS).

III. State Estimation for NEPTUNE

The NEPTUNE system will face the challenge of having fewer measurements than a conventional terrestrial power system. The proposed power system design presents the further challenge of not having the ability to communicate with the BU's to operate the switches, or retrieve data. Even if measurements are conducted in the BU's, the information cannot be transmitted to the shore stations for use by PMACS. The result is a situation where the backbone currents and voltages must be estimated using measurements from the science nodes and the shore stations. The task is analogous to determining the state of a transmission system from measurements made in the distribution system, which is an unusual task for a power system.

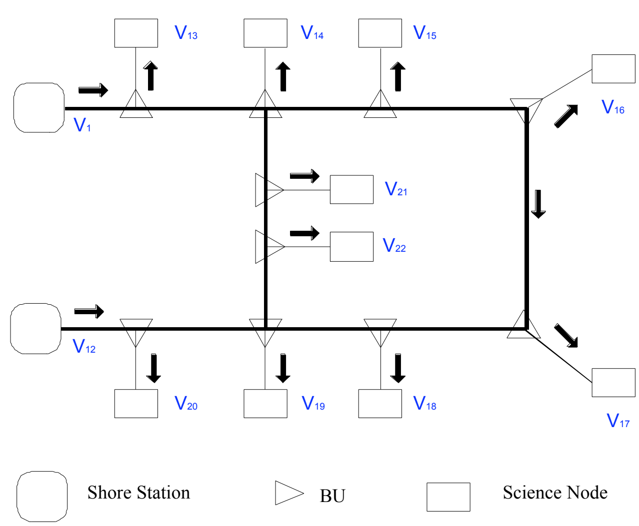

Figure 2 A simplified NEPTUNE model

In order to demonstrate the implications of having of no communications with the BU's, a simplified model of the NEPTUNE power system will be used, Figure 4.

Figure 4 shows a simplified system composed of 2 shore stations, 10 science nodes, and 10 BU's. Included in the figure are the voltage and current measurements that are made at the shore stations and at the science nodes.

First, it is seen that each of the measurements that can be made can also be expressed in terms of BU voltages. (If so, it is reasonable to expect the converse to be true: the unobservable BU quantities can be estimated from the measurements.) As an example the voltage and current measurements at a single science node will be calculated, Figure 5.

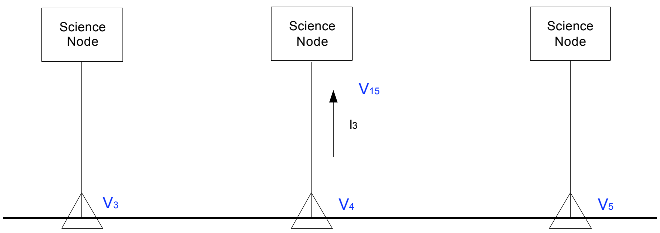

Figure 3 Known and unknown quantities in a string of nodes

Through the use of Kirchhoff's current and voltage law, it is shown that the current flowing into the science node, as well as the voltage is given by Equations 3.1 and 3.2.

$$I_3 = \left(\frac{V_4 - V_5}{R_{45}} - \frac{V_3 - V_4}{R_{34}} \right)$$

(3.1)

$$V_{15} = V_4 + \left(\frac{V_4 - V_5}{R_{45}} - \frac{V_3 - V_4}{R_{34}} \right) * R_{4(15)}$$

(3.2)

Equations 3.1 and 3.2 illustrate the manner in which the science node voltages and currents are expressed as functions of BU voltages and cable resistances. By relating these equations to Equation 2.6, it is seen that the values measured at the science node form the matrix Z^{meas}, the BU voltages form x^{est}, measurement errors form the R matrix, and the values of line resistances and their interconnections form the coefficient matrix H.

If all measurements could be expressed in terms of the unknown BU voltages and the H matrix, then the relation in Equation 2.6 would hold true. When all measured voltages and currents are expressed in the form of Equations 3.1 and 3.2, the known shore station voltages and voltages at the science nodes adjacent to the shore stations will appear in the calculations. The appearance of these measured values lead to the formulation in Equations 3.3 and 3.4.

$$Z^{meas} = Hx^{est} + CZ^{meas}$$

(3.3)

$$Z^{meas} = (I - C)^{-1} Hx^{est}$$

(3.4)

Following the steps of Equations 3.3 and 3.4, one obtains

$$x^{est} = \left[H^T \left((I - C)^{-1} \right)^T R^{-1} (I - C)^{-1} H \right]^{-1} \left[H^T \left((I - C)^{-1} \right)^T R^{-1} Z^{meas} \right]$$

(3.5)

Equation 3.5 is similar to Equation 2.6 if H is replaced with $\hat{H}$.

$$x^{est} = \left(\hat{H}^T \cdot R^{-1} * \hat{H} \right)^{-1} \cdot \hat{H}^T \cdot R^{-1} \cdot Z^{meas}$$

(3.6)

$$where: \hat{H} = (I - C)^{-1} H$$

One issue of importance is the rank of (I-C) Since the C matrix has values only on the rows/columns that have connections to the shore stations, C is sparse. When C is subtracted from the identity matrix I it is possible for the square matrix (I-C) to become singular. The problem of (I-C) being singular is a result of the ordering of the state estimation Equations and not a result of a problem with the power system.

The problem of singularity can be avoided by careful formulation of the state estimation equations, (i.e. 3.1 and 3.2) when forming the C matrix. Using the simplified system in Figure 4 there are only 8 rows that contain non zero elements. Each of the 8 rows only contain a single non zero value. Equation 3.7 gives a further simplified example of the I-C matrix that will be used to illustrate the singularity problem.

$$(I - C) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & .25 & 0 \\ 0 & 4 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(3.7)

Equation 3.7 is the representation of a system that is defined by only 4 equations containing 4 variables V_1, V_2, V_3, and V_4. Observation of Equation 3.7 shows that the 2nd and 3rd columns of the matrix are linear combinations, resulting in a singular, non-invertible, matrix. If the 4 equations are left unchanged, and their order changed, the result is 3.8.

$$\left(I - \hat{C}\right) = \begin{bmatrix} 1 & 0 & .25 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 4 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(3.8)

By changing the order of the equations, switching the 1st and 2nd rows, the matrix is no longer singular. The switching of the 1st and 2nd rows reorders the output variable but does not change the results of the calculations. The variables of Equation 3.7 are ordered as V_1, V_2, V_3, V_4 and 3.8 is ordered as V_2, V_1, V_3, V_4. Careful ordering of the state estimation Equations, 3.2 and 3.3, in this manner will prevent the problem of the matrix (I-C) being singular.

IV. State Estimation Results for NEPTUNE

The first step in evaluating the results of the state estimation algorithm is to generate data using a power flow program. For a given load and system topology, the power flow algorithm will give the voltages and currents at the science nodes as well as the BU's. With the voltages and currents at the science nodes as inputs to the state estimation algorithm, the voltages at the BU's can be calculated and compared to the actual values as generated by the state estimation algorithm. The result is that the voltages calculated at the BU's agree with those calculated by the power flow to several significant figures. This agreement indicates that the algorithm for state estimation will work for the limited number of measurements present in the NEPTUNE system, when there is no measurement error present.

The next step is to introduce an error in the voltages and currents measured at the science nodes. If the state estimation algorithm is functioning properly then the error in voltages calculated at the BU should be roughly equivalent to the error of the measurements at the science nodes [7].

Since the NEPTUNE system has not been constructed, simulation will be used to test the validity of the state estimation algorithm. A power flow solution is calculated for the simplified system that gives the exact values for all system voltages and currents. The voltages and currents at the science node are then summed with a Gaussian distribution of errors to simulate the actual measurement devices. These values, with the Gaussian error included, are the then used to estimate the voltages at the branching units. The estimated values of the BU voltages will *not* exactly match the BU values because of the errors introduced into the science node measurements.

For example; if there is a 1% error in the voltage and current measurements made at the science nodes, then there should be a roughly 1% error between the estimated and actual BU voltages. Table 1 gives the calculated and actual values of voltage at the BU's for a 1 % measurement error at the science nodes. From Table 1 it can be calculated that the average error between the actual and calculated value of BU voltages is 81.6 volts. The average measurement error that was introduced at the science node was 91.1V. The comparison of the actual and calculated voltages shows that the state estimation algorithm can effectively estimate the voltages at the BUs even in the presence of measurement error.

While it is possible to compare the actual and calculated values of the BU voltages in simulation, it will not be possible to do so in the NEPTUNE power system. Instead we must use a two step approach to generate a meaningful comparison. The first step is to calculate the voltages at the BU's using

Table 1

BU	Estimated BU Voltage	Actual BU Voltage	Error
1	9914	9735.2	178.8
2	9589	9524.5	64.5
3	9579.8	9418.6	161.2
4	9344	9365.5	-21.5
5	9271.6	9365.5	-93.9
6	9403.7	9418.6	-14.9
7	9614.5	9524.5	90
8	9640.7	9735.2	-94.5
9	9529.7	9472	57.7
10	9432.8	9472	-39.2

Equation 3.6. The second step is to work backwards and use Equation 3.3 to calculate the voltages and currents at the science nodes using the estimated BU voltages. When this approach is followed it is possible to compare the voltages and currents measured at the science node to those calculated using the estimated values of BU voltage, and thus to generate the residual J(x) given by Equation 2.3.

V. Bad Data Identification and Topology Errors

In a state estimation algorithm there are two major possible sources of error; measurement error and topology errors.

All voltage and current measurements contain uncertainty. When measurements are used to estimate values the uncertainty in the initial measurements propagates through the equations and causes uncertainty in the estimation. A formulation for the propagation of error, assuming a system of 3 variables, Equation 3.2, is given by Equation 5.1 [7].

$$\sigma_{V_{15}}^{\ 2} = \left[\sigma_{V_3}^{\ 2}\left(\frac{\partial f(V)}{\partial V_3}\right)^2 + \sigma_{V_4}^{\ 2}\left(\frac{\partial f(V)}{\partial V_4}\right)^2 + \sigma_{V_5}^{\ 2}\left(\frac{\partial f(V)}{\partial V_5}\right)^2\right]$$

(5.1)

where:

$f(V)$: Equation 3.2

$\sigma_{V_{15}}$: Variance of error of V_{15} (in %)

σ_{x_n} : Variance of error of the measured voltages

The propagation of uncertainties is especially important when in the second step of estimating the validity of the estimated measurements. In the second step, the voltages and currents at the science nodes are calculated using the *estimated* BU voltages. From Equations 3.1 and 3.2 it was shown that all of the current and voltage measurements made at the science nodes can be expressed in terms of the BU voltages. It has also been stated that the uncertainties in these estimations are on the same order as those as the measurements made at the science nodes. The problem of bad data arises when a measurement value is well outside the expected variance of the uncertainties. There is an error. The issue of identifying this situation can be resolved using well-known methods such as a chi-squared test.

By referencing _^{2} tables [7] it is possible to determine the probability of a science node measurement differing from the estimated value by a given amount. When referencing _^{2} tables the probability of a residual exceeding a given value is listed as a percentage. As an example: for a system that contains 14 more measurements than unknowns, degrees of freedom, there is a 1% chance of a normalized residual being greater than 29.148. The percentage chance that is examined, 1% in the previous example, is a value than is selected by the operators. Values ranging from roughly 0% to 100% can be found in _^{2} tables.

In order to perform an accurate state estimation it is essential to have correct topological information [8, 9, 10]. If the assumed topology is incorrect then the error it introduces can appear as error due to bad measurement. The inability to observe the BU's presents a challenge. Since there is no direct indication of the backbone breaker status, an alternate method of topology identification must be devised.

Unlike conventional state estimation with non linear equations, state estimation for a DC system, with linear equations, is not an iterative process. The non iterative nature of the DC calculation allows for multiple state estimation calculations in the time that it takes to do a single iterative AC state estimation. Short calculation times combined with the relatively small number of backbone breakers allows PMACS to do a state estimation for the assumed topology as well as all possible single or double contingency possibilities.

A single breaker status error is considered to be a single contingency. When a breaker is open, it is not readily apparent from which side the power will be supplied. (From Figure. 3 it can be seen that when a backbone breaker is open the power will be supplied from the side that happens to have the most negative voltage.) For this reason, it is necessary to perform a number of additional state estimations: the number is equal to double the number of backbone breakers. Each state estimation calculation corresponds to a hypothesized system topology where power is served from a single side of the breaker. This quantity can be reduced by using a logic-based system to determine combinations that are not possible. When a calculated residual, Equation 2.3, exceeds the _^{2} values, comparison with the contingency state estimation solutions can help to resolve whether the error is a measurement error or a topology error.

VI. Conclusions

This paper represents the continuation of work that has been in progress for over two years. The major contribution of this paper is that it outlines a functional algorithm for state estimation in a highly interconnected direct current system with a high degree of unobservability. In addition to the unique interconnected direct current configuration, the limited number of measurements points is also addressed.

The well known issues of bad data identification and errors in the system topology are also examined and a proposed method of solving the problem is proposed.

There is still a great deal of work that remains to be done before the ideas presented here will be implemented in the actual field implementation of the algorithm.

The work presented in this paper is directed at only one of the many challenges that must be overcome in order to develop a fully functional power system for NEPTUNE. Other issues that must be addressed are security assessment, operational control, protection, and fault location. Due to the unique nature of the NEPTUNE power system conventional methods do not readily supply the answer to these questions for NEPTUNE. Research has been conducted in these areas and future papers addressing these issues are expected.

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VIII. Biographies

Chen-Ching Liu received his BS degree in 1976 and his MS degree in 1978 both in Electrical Engineering from The National Taiwan University. In 1983 he received a Ph.D. from University of California, Berkeley. Chen-Ching Liu is currently a Professor of Electrical Engineering and Associate Dean of Engineering at the University of Washington. Dr. Liu serves as Director of the Advanced Power Technologies (APT) Consortium and Electric Energy Industrial Consortium (EEIC) at the University of Washington.

Kevin Schneider received his BS degree in Physics in 2001 and his MS degree in Electrical Engineering in 2002, both from the University of Washington in Seattle. Currently he is a research assistant working under Chen-Chin Liu at the University of Washington. His main area of research is the NEPTUNE power system and is currently pursuing a Ph.D. in Electrical Engineering.

Harold Kirkham (SM) received a B.Sc. in 1966, and a M.Sc. in 1967 both from the University of Aston in Birmingham, England. In 1973 he received a Ph.D. from Drexel University in Philadelphia.

In Philadelphia, in the late 1960s, he worked on the AC/DC Research Project of the Edison Electric Institute, and continued an interest in the topic of combined AC/DC systems into his Ph.D. work. From 1973 until 1979 he was with American Electric Power, responsible for the data acquisition system at their UHV station in Indiana. In 1979 Dr. Kirkham joined the staff of the Communications and Control for Electric Power Systems project at the

Jet Propulsion Laboratory in Pasadena, CA. He managed the project from 1984 until it ended in 1995. He is presently a Principal in the Center for In-Situ Exploration and Sample Return at JPL.

Dr. Kirkham's research interests include both power and measurements. He has developed a series of instruments to measure electric fields, and is the chairman of the IEEE Power Engineering Society's Instrumentation and Measurements Committee. He is presently manager of the NEPTUNE power system project, a development being done in collaboration with the University of Washington.

Bruce M. Howe received the BS degree in mechanical engineering and the MS degree in engineering science in 1978 from Stanford University, and the PhD degree in oceanography in 1986 from the Scripps Institution of Oceanography, University of California, San Diego.

While at Stanford Dr. Howe developed laser doppler velocimetry (LDV) instrumentation for air-sea interaction experiments. From 1979 to 1981, he was a Research Associate at the Institut für Hydromechanik, Universität Karlsruhe, working on LDVs for use in the atmospheric boundary layer.

While at Scripps and since then he has worked on ocean acoustic tomography, most recently on the Acoustic Thermometry of Ocean Climate (ATOC) project. A current interest is cabled seafloor observatories, specifically the NEPTUNE project focused on the Juan de Fuca Plate. He is presently a Principal Oceanographer at the Applied Physics Laboratory and a Research Associate Professor in the School of Oceanography, both at the University of Washington, Seattle