The Design of the NEPTUNE Power System

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Abstract—The proposed NEPTUNE observatory will include about 30 locations on the Juan de Fuca plate where scientific instruments can be connected for communication and power. The NEPTUNE power system is required to make available at each location the largest amount of power possible, using conventional submarine telecommunications cable. The power delivery system is based on the use of a standard cable, but it is used in an interconnected network in order to maximize both reliability and power level. The cable will be energized with medium voltage -10 kV dc and have parallel loads, a combination that has never been built before as an interconnected network. During normal operation, it is calculated that a power level of over 5 kW can be delivered to each of the 30 nodes. Should it be needed, as much as 40 kW can be delivered to each of 3 nodes on the far west of the network, 500 km from shore, provided the power on all the other nodes is reduced to 1 kW. These power levels and distances are considerably greater than has been achieved in previous undersea observatories. The design of the sub-sea node is based on the use of switched-mode power supplies with series-connected inputs and parallel connected low voltage outputs. The ocean is used as a return path. Consideration of the reliability of the system plays an important role in the design of the power system. A scheme of protective relaying will enable the delivery system to continue operation even with faults in part of the network.

I. INTRODUCTION

The proposed NEPTUNE observatory [1, 2] will include about 30 locations under the Pacific on the Juan de Fuca plate, west of the U.S. and Canadian west coasts (Fig. 1). At each location, scientific instruments can be connected to fixed nodes for communication and power.

The NEPTUNE power system is required to make available at each location the largest amount of power possible, using, for cost reasons, conventional submarine telecommunications cable.

The level of power needed is much more than for typical submarine telecommunications repeaters, which operate at a fixed current of about 1 A. It is more, too, than required for science instruments only. Lights for television, energy for experiments involving heat transfer, and energy for charging batteries are also needed.

The design that has evolved to meet these needs is novel in several respects. The power delivery system will be operated as an interconnected network in order to maximize both reliability and power level. The cable will be energized with dc. Although the concept has been discussed for many years, dc systems have never been operated before as interconnected networks.

II. TRADE-OFFS

Power from the shore is inserted into the network at medium voltage (MV; defined by IEEE as 2.4–72.5 kV). As a practical matter, the cable insulation on a typical telecommunications cable is rated for around 10 kV, so this value is assumed as an upper limit for the NEPTUNE backbone. The resistance of a typical cable is so high (about 1 Ω/km) that over the distances involved in NEPTUNE, the current is limited by the cable-volt-drop to about 10 A.

Given these constraints, the basic trade-offs are as follows:
- ac or dc on the cable?
- interconnected or radial network?
- series or parallel connected loads?

These questions are addressed in detail elsewhere [3]: they will be summarized here.

The question of ac or dc on the cable reduces to a relatively simple cost calculation. If ac were used (at least at 50 or 60
Hz), the charging current of the cable capacitance would be so large as to require compensation by shunt inductors. An order of magnitude estimate of the cost makes this alternative much more costly than the use of dc.

The use of very low frequency ac is somewhat more attractive. Supply at (say) 0.1 Hz would have the advantage of low charging current, and the further advantage of avoiding the various cable insulation problems that affect dc cables. However, at the relatively low voltages expected in this cable, these problems are solvable. Further, the use of very low frequency ac would require additional complexity in the nodes, as transformers for such frequencies are not feasible. On balance, it was felt that the complexity of ac/dc conversion could not be justified.

The decision whether the network should be operated radially or interconnected has significant impact on the reliability (availability) of the delivery system. In terrestrial power delivery systems, only the distribution system is operated radially; the remainder is interconnected. It is this interconnection that has improved the reliability to the point that the great majority of power outages are due to distribution system problems.

While it is true that operation of terrestrial power systems closer to their maximum power limit has resulted in the fewest outages having a more widespread effect, analysis also shows that deliberate load shedding could be employed to avoid cascading [4]. This is a possibility that will be borne in mind for NEPTUNE. Some loads are readily deferred (battery charging, for example) and others may be considered of low priority.

In order to be both series-connected and a network, a new scheme would have to be developed in order to split the power at a branch. This hypothetical new block would have to recognize sources and loads (the answer might change as loads changed over the lifetime of the project) and then deliver the same current to each of the outgoing cables, at reduced voltage. While such a device is feasible, the network that used it would still suffer the inefficiencies of a series system, and the power level that could be transmitted would be so much lower than a parallel scheme could transmit, that a parallel scheme was chosen early in the discussion of trade-offs for NEPTUNE.

III. SYSTEM DESCRIPTION

The NEPTUNE system one-line diagram is shown below (Fig. 2). The arrows on the one-line diagram show the direction of power flow, assuming all loads are equal.

A. Switching and Sectionalizing

The multiple possibilities for sectionalizing to isolate faulted nodes and faulted cable sections are also evident. In order to do this, some means of switching the faulted section must be provided. At this time, the decision has not been made whether circuit breakers or switches will be used. Circuit breakers have to interrupt fault current: in the case of a controlled system such as this, the fault current will be about the same as load current. Nevertheless, there may be some reliability advantages to switching only when the system is de-energized.

If this option is chosen, it will be necessary to implement a communication system that can operate without the nodes being active. A field-bus system operating over a king-wire is being considered. While slow (we estimate at most a few kbits/second), such a scheme would constitute a useful means of access into the power network, and possibly the communication scheme.

Each bus in the one-line diagram represents a switching arrangement. For the simple cable-in/cable-out locations (most nodes), a pair of diodes can be used to replace a switch (Fig. 3). The advantage is the reduced number of moving or controlled parts.

Opening the single breaker in Fig. 3a has the same effect as opening one of the breakers in Fig. 3b: the two parts of the cable are isolated from one another, but the node supply bus can take power from whichever side is still connected. The double-bus double-breaker configuration in Fig. 3c has the advantage that it permits full operation of the junction even if one of the breakers fails, whether it fails open or closed. In a system designed for a long life, and with restricted access for repair, such fault tolerance may be important. The arrangement can be extended to 4 or more lines at a node.

B. Protection scheme

Complementing these various switching schemes will be a protection system based (somewhat loosely) on utility power system practice. The purpose of the protection scheme is to detect faults in the network, and minimize their effect by operating the appropriate switches.

There are several ways that faults can be detected. The simplest is based on the concept of overcurrent: a circuit that normally handles a current of (say) 10 A can be assumed to be faulted if the current suddenly becomes 20 A. A fuse is an example of an overcurrent protection device. (Fuses are ruled
out here because they are not resettable, do not work well with
direct current, and are not likely to discriminate adequately.

A problem with this approach is that it does not distinguish
faults that are close from faults that are remote. More than a
minimum amount of the system may thus be disconnected.

By using information from several parts of the power
system, the protection scheme can do a better job of
discrimination between faults.

For example, a distance relay gives better discrimination.
In this device, a computation based on the measurement of both
voltage and current is used to estimate the fault location
relative to the point of measurement.

An even better protection scheme, and one that could be
used in NEPTUNE, is the differential scheme. In this approach,
the current at one end of the section is compared with the
current at the other end. If there is a difference, there must be
a fault between the two points of measurement. This kind of
protection relies on the existence of a fairly fast communication
connection between the two ends. In NEPTUNE, this
connection can be assumed to exist in the form of the

NEPTUNE communication system. If the fault removes the
"best" NEPTUNE connection, land-based portions of the
internet could be used to complete a communications circuit.
A differential protection scheme is a viable possibility.

A generic block diagram of such a protection scheme is
shown in Fig. 4. Monitored parameters are used continuously
to calculate the quantities on which the action decision will be
based. For example, this may mean computing the location of
the fault. Based on this calculation, the relay will decide
whether to trip a circuit or not.

Fig. 3. Alternate ways to implement sectionalizing at a
simple node

Fig. 4. Generic protection system functional block diagram

In practice, because a fault might prevent or delay com-
munications, it is planned to adopt the utility practice of having
layers of protection. NEPTUNE's protection scheme could
include differential, distance, and overcurrent relaying. This
way, the first (and best) line of defense would be the
differential scheme; if the fault causes loss of communication,
the distance relaying would operate; if the distance relaying
failed, the overcurrent system could save the day. Because the
loads are expected to be far more deterministic than those of a
typical utility, overcurrent protection levels can be set quite
close to the normal load values.

The protection function will be built into the junction
boxes. Some aspects cannot easily be changed after install-
ation, for example, a method to isolate faulted components must be
provided for the system to function. On the other hand, some
of the settings can be changed, for example, by means of
updatable data tables.

The hardware may be quite complex. The protective
relaying system must use independent sensors wherever
possible, and be capable of dealing with failures inside the
protection scheme itself (such as failed circuit breakers).
C. Power Management System

While the power system must operate autonomously (that is, without operator intervention), it must be capable of furnishing information to the system operator that could be used to modify the way operation is carried out. Some level of supervisory control, supported by an internal data acquisition system, is therefore required.

The management system will likely monitor the same parameters monitored by the metering scheme, and may share the primary transducers. Most probably it would store the data for off-line analysis. In addition, it would scan the data for the on-line generation of alarms.

A maintenance alarm would be generated when a condition existed that was not serious enough to warrant action by the protection system, but was serious enough to justify operator intervention. An excess power consumption by a particular load might be an example, if the power level did not result in an overload and trip.

An operation alarm would be generated whenever a more serious condition was encountered.

The design and implementation of the power management system must be integrated with the protection scheme. Resources may be shared with this, or with the metering scheme.

D. Deliverable Power

To better understand the possible parameter space for the NEPTUNE power system design, we have simulated various configurations of the system, varying nominal shore voltage, cable resistance, and loads at each node.

The basic laws that govern the steady-state flow of power within a dc electrical network are Kirchhoff’s current and voltage laws and Ohm’s law. Here, we have an additional constraint: the power, \( P = VI \), withdrawn from each node is prescribed. To handle the nonlinearity that results in the equations, the problem is solved by iteration. The initial voltage used at all the nodes is the shore station voltage, and all the initial currents are zero.

The first set of simulations assumed the two shore stations (Nedonna Beach and Victoria) operating at 10 kV and using 1 \( \Omega \)/km cable. As the load power is increased from 1 kW to 6.7 kW at each node, the efficiency falls from 97% to 63% (Fig. 5). To some extent, efficiency can be used as a surrogate for stability. As was shown in an earlier paper [3], any power system is capable of becoming unstable as its maximum power transfer capability is approached. The usual way of detecting this approaching instability is to examine the eigenvalues of the system Jacobian. An alternative is to look at the convergence of the load software. The idea of using efficiency is only workable here because it can readily be calculated during the simulation. The 6.7 kW value is close to the maximum possible power before the system (and code) go unstable. The minimum voltage occurs in the southwest leg.

If the shore voltage is increased to 15 kV, the efficiency increases from 63% to 90% for the same useful power (6.7 kW), showing that this level of power is not close to the system limit. In fact, the maximum possible power in this case is about 15.2 kW at each node.

If the cable resistance is then lowered to 0.7 \( \Omega \)/km the efficiency increases from 60% to 82%. The maximum possible power per node is 21 kW, for the “best” cable – 0.7 \( \Omega \)/km and 15 kV. As for the 10-kV cases, the minimum voltage in the system occurs in the southwest leg. If we revert to 10 kV at the shore stations, but keep the 0.7 \( \Omega \)/km value for resistance, the maximum possible power is 9.6 kW per node.

Two cases were considered where three 1000-km spur cables are added to simulate possible cables to Ocean Weather Station PAPA to the northwest, the deep Northeast Pacific (dubbed UNCLE), and south to California. In these two cases, the loads are not evenly distributed; at eight nodes that are considered by some to be scientifically more interesting, the load is higher. The eight nodes are: Juan de Fuca Strait, Endeavour Ridge, Axial Volcano, Hydrate Ridge, and at the end of each of the three long spur cables. In the first of these cases, 10-kW loads are required at the selected 8 nodes, and 5 kW at the rest. This produces a stable solution with an efficiency of 74%. In the second case, 14 kW are required at the selected 8 nodes, and 2 kW at the rest. This produces a stable solution with efficiency of 71%.

Reverting to the standard 30-node configuration (Fig. 1), 0.7 \( \Omega \)/km, and 10 kV, we wished to know how much power could be delivered to a small number of nodes located on the ridge. We found that it was possible to deliver 40 kW to each of the three nodes at the southern end of the Juan de Fuca Ridge (Axial Volcano and the two adjacent nodes to the south), while at the same time delivering 1 kW to all the other nodes. In this case, the efficiency is 66%, suggesting that a slightly higher power level yet is possible. This high level of power (40 kW) has implications for the node design, of course. Should all nodes be rated for this level of power? Should any?

We also explored the possibility of only one active shore station, still using 0.7 \( \Omega \)/km and 10 kV. If only Nedonna Beach were active, 5.6 kW maximum can be delivered to all the nodes. If only Victoria were active, 3.9 kW maximum could be delivered to all the nodes.

In both cases, the minimum voltage is at the node farthest from the shore station (i.e., the ends of the northern and southern spurs, respectively). Repeating the scenario in the preceding paragraph, one finds that the maximum power at the distant three nodes is 30 kW if only Nedonna Beach is active, and 21 kW if only Victoria is active.
These results show that it is fair to regard each shore station power supply as a backup for the other. Even with only one shore station supplying power, a significant amount of power can be distributed to the junction boxes around the seafloor using cable with readily obtainable parameters (i.e., cable resistance and operating voltage). These power levels and distances are considerably greater than has been achieved in previous undersea observatories. Because the present topology is reasonably robust against the loss of one shore station, it may be that it is unnecessary to provide an uninterruptible power supply (UPS) at each station. This matter will receive further consideration.

While the focus of this brief discussion has been on the maximum possible delivered power, one would clearly not run an actual system near this operating point, because of the associated voltage instability. The power levels given here are, however, considered feasible.

1. The isolation transformers. Some of these will have a working 10-kV dc voltage between the primary and secondary windings. For testing purposes a maximum of 20 kV dc will be applied. The switching waveforms across the primary and secondary windings are no more than 200 V. These features allow for standard and simple construction methods of the isolation transformers.

2. The circuits for feedback, clock, and drive signal for the power MOSFETs. These can be achieved either by optical or magnetic (transformer) means.

All the stages are synchronized to the same clock and receive the same error feedback signal from the output voltage. The current feedback loop allows for minor adjustments for each stage in the duty cycle to ensure equal sharing of voltages and currents among all the stages, regardless of variations in component tolerances.

![Diagram of converter](image)

**Fig. 7.** One converter stage

The converter topology used for each stage is the buck-derived, two-switch forward converter. This has the lowest stresses among all isolated converter topologies and, hence, high reliability (Fig. 7). Each stage is designed to operate from an input voltage range of 100–200 V. Below an input voltage of 100 V, a stage drops out. With 50 such input stages, the dc/dc converter operates from an input voltage in the range 5–10 kV and drops out below 5 kV.

The purpose of the input filter is to attenuate the high-frequency switching ripple. The filters used provide an attenuation of 100 dB resulting in an input ripple current of 30 μA.

To validate the design, a Pspice simulation was performed using four stages. On the input side, four stages were connected in series and on the output side, two series-connected stages were connected in parallel. The input voltage was set at 800 V and the output voltage was set at 100 V and 2 A. Between the voltage source and the converter, a 100-km transmission line was used with the following characteristics: 1 Ω/km, 0.2 μF/km and 1 mH/km. The component values for the inductors, capacitors, and resistors were varied within a tolerance of 10%. The waveforms obtained show that the input voltages to all the stages are nearly identical (Fig. 8). The currents in the output inductors are also identical.

### IV. RELIABILITY

One of the advantages (and requirements) of a cabled observatory such as NEPTUNE is low maintenance over its planned life. A performance goal was set of no more than one node repair needed every 2 years at any of the 30 nodes over
the planned 30 year life. To achieve this goal, consideration of
the reliability of the system played an important role in the
design of the power system. A scheme of protective relaying
will enable the delivery system to continue operation even with
faults in part of the network. Within each node, standby
redundant converters will be used, so that with readily
achievable MTBF figures, the overall system goal is met.

A separate, but integrally related, subject is the availability
of the overall NEPTUNE system. Repair missions will require
some lead time to acquire the resources, and a repair mission
will only be possible during an abbreviated portion of the year
(from May through September). Hence, even when failures
occur and repairs are required, it may take more than 6 months
to accomplish. The NEPTUNE system must be robust to these
failures. Consequently, it is designed so that most failures that
occur will only result in loss of redundancy. Most single points
of failure that are in the system can be isolated and result in the
break in the cable that does not short to the ocean or an open
failure of a breaker will not cause any science loss since the
power supplied from a single shore station is sufficient to
provide power to the entire undersea configuration. Likewise,
a short to sea within a node power system can be isolated by
opening the breakers at the nodes on either side.

There will likely be two power converters in parallel in a
node for redundancy. They can be isolated by opening two
breakers if a converter happens to fail. If, upon analysis, the
two-converter design proves not sufficiently reliable, then a
third converter can be added in parallel to provide the
reliability needed. The design would contain an additional on-
line spare. The startup supply element should be simple
enough to be highly reliable, but could also be redundant, one
in series with each converter. In the current design, the only
single string elements of a power node are the primary and
secondary supply busses.

Given the high cost of repairing the system, both in terms of
budget and time, there is a strong impetus to make the system
robust and reliable. As noted above, additional redundancy
may be needed to meet the reliability goal or may be
determined to be cost effective when traded against the cost of
repair. Other options are also available to provide assurance.
These include:

- Assuring that the electronics designs are not using parts
close to or above their maximum ratings
- Using higher quality (e.g., military or space qualified)
parts
- Maintaining the temperature at low levels (which
should be fairly easy with a convenient heat sink via
the ocean)
- Performing worst case analysis on the circuits to assure
that parametric shifts over the life of parts does not
result in out-of-specification performance.

From the network point of view, reliability is gained by
operating the power delivery scheme as a network. A scheme
of protective relaying will enable the delivery system to
continue operation even with faults in part of the network.

A Monte Carlo simulation of the 32-node network was
performed to obtain estimates of expected system availability,
given estimates of mean-between-failures (MTBFs) of
cable sections and node breakers. We assume the reliability of
a breaker is an exponential based on 1,000,000 hours MTBF
and each connecting cable is exponential based on 10,000,000
hours MTBF and each repair takes 3 months. The two shore
station nodes are assumed perfect, and all other aspects of the
nodes are ignored. A system lifetime of 30 years is used. 1000
realizations were performed with results shown in Fig. 9.

For approximately 85% of the realizations of the possible
future states of the system, the availability is greater than 0.9,
i.e., during the 30-year lifetime, at most 3 years are spent in
repair. With the system under repair due to component failure,
availability is counted as zero even though most of the nodes
are functioning. Most of the time, at least 31 nodes are
available and functioning, occasionally 30, 29, or 28, and
rarely fewer than 28. For example, in 95% of the cases, the
availability was greater than 0.967, i.e., only one node down.
V. CONCLUDING REMARKS

Some important decisions have been made — the NEPTUNE power system will be dc, will operate as a network, will have parallel loads — and are documented elsewhere. Some crucial decisions remain before the design work can continue very far. For example, what voltage levels must be available on the output of the dc/dc converter? Will there be a king-wire communication system? Will the double-bus double-breaker approach be used even at a simple node? Some of these questions have been discussed in this paper — their resolution will be documented in the growing library of documentation that NEPTUNE is accumulating.

A good deal of design work remains. Some of this work is at the system level, and some at the subsystem and even the component level. The recent addition of Drs Chen-Ching Liu and Mohamed El-Sharkawi at UW, Tim McGinnis at APL, and of George Fox at JPL, increases the power group’s strengths across this spectrum. We feel we have assembled a team with wide-ranging expertise, and we are moving forward with growing momentum.

For the NEPTUNE project, the power system is in many respects the pacing item. The task of designing the dc/dc converter is in hand and we plan to have a prototype within a year. Other elements of the work, for example, the operations software and some elements of the protection system, may not be ready for a year after that. The challenge of meeting the goals will, we anticipate, be rewarding. That we are contributing to an important new facility is even more so.

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