Power System Considerations for Undersea Observatories

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***Abstract*—Power systems for undersea observatories combine ideas from terrestrial power systems and switching power supplies with experience from undersea cable systems. Basic system tradeoffs for various design decisions are explored in this paper. First, design questions including whether the power delivery should be alternating or direct current and a parallel or series network are examined. This introduces the question of maximum power delivery capability, which is explored in depth. A separate issue, the negative incremental resistance presented to the delivery system by the use of constant-voltage converters, is examined, and the resulting dynamics explored by simulation.**

***Index Terms*—DC/DC converter, dc power systems, medium voltage dc converters, ocean observatories.**

I. INTRODUCTION

SCIENTIFIC interest is growing in the application of undersea cabled observatories (see [1] and [2]). The Long-term Ecosystem Observatory (LEO-15) is an example with two nodes in 15 m of water 7 km off the New Jersey coast [3], [4]. It supports a variety of science instrumentation including a winched conductivity/temperature/depth instrument, video, and autonomous undersea vehicles. LEO-15 makes it clear that power is required not just for electronics but also for motion, light, and heat transfer. The engineering of the power system for such applications is discussed in this paper.

At present, all subsea observatories use a single cable from shore for power.[1] Not only does this make such systems vulnerable to single-contingency outages, it severely limits the size of the observatory or the amount of power that can be delivered.

II. APPLICATION

Because of its size (around 3000 km of cable is planned; see Fig. 1), the proposed NEPTUNE observatory [5] on the Juan de Fuca tectonic plate is required to have more than one power source. Fig. 1 shows how interconnections are planned to create a network. Power infeeds from shore at medium voltage (MV; the IEEE definition is 2.4–72.5 kV) supply a number of junction boxes via a single conductor cable. For cost reasons, the cable will be standard, single-conductor submarine telecommunications cable operating with a nominal rating of 10 kV. At each junction box, power is converted down to low voltage for science users. The junction boxes will serve both as communication add/drop points for science users and as repeaters; they will be spaced less than 100 km so that separate optical amplifier repeaters are unnecessary.

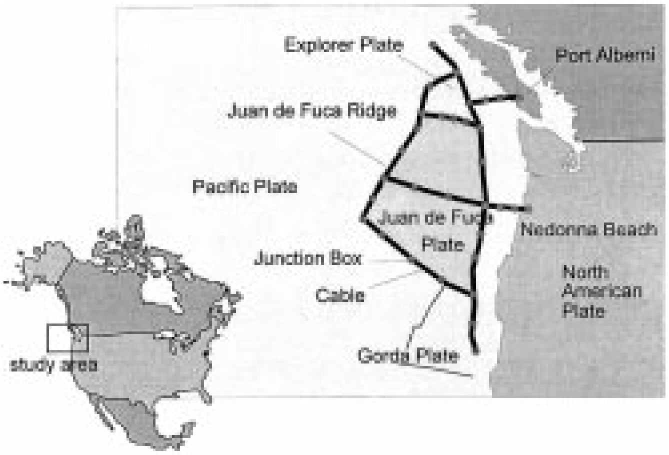

Fig. 1. The proposed NEPTUNE observatory in the northeast Pacific.

The power converter is unlike that in a conventional telecommunication repeater, as a parallel power scheme is used. Therefore, the full supply voltage is applied to the converter. A high-efficiency dc/dc step-down converter is being designed for the purpose and will be described elsewhere. It is hoped that this aspect of the power system will be widely useful.

Some junction boxes will also branch the cable. This is done in order to maximize the availability of the system in the event of cable damage or node failure. The use of a network in this way creates redundant paths to most nodes, so that while power and bandwidth may be reduced by a fault (e.g., a cable break), they are not reduced to zero. On land, it is this kind of redundancy in the transmission system that keeps the availability of utility power high; lack of this redundancy in the distribution system accounts for 70% of power outages.

Any future undersea observatory would clearly benefit from this kind of fault-tolerant approach: repairs to ocean-bottom facilities are generally expected to incur very long delays and high cost. If much (or even all) of the observatory can be kept in operation during and following an outage, the return in terms of science could be significant.

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[1] See, for example, http://adcp.whoi.edu/LEO15/index.html and http://www.soest.hawaii.edu/HUGO/hugo.html

This paper will discuss how ideas and approaches from terrestrial power systems can be adapted for an underwater observatory. While the discussion is intended to be fairly general, specific conclusions about the recommended approach are most appropriate for the proposed NEPTUNE observatory that will provide total power of O(100 kW) over a large area using a networked topology. The requirements of such an observatory and the constraints imposed by the application differ enough from terrestrial power systems that a review of many basic system aspects is justified.

We recognize that some of our recommendations cannot be implemented at observatories where existing infrastructure must be used to deliver power to reduce the total cost at the possible expense of efficiency. However, the tradeoffs discussed in this paper have wider applications, particularly for new systems, and should be considered for other observatories as well as tethered vehicles.

A. AC or DC?

For future undersea observatories, both ac and dc delivery are viable. Most land power systems are overhead and use alternating current. This allows the use of transformers and the efficiency of high-voltage transmission. Whether ac or dc, an undersea observatory would not use a conventional transformer, because of size and magnetostriction problems. The nodes, whether ac or dc, would thus use essentially similar switching converter technology, and the tradeoff must be done on system considerations.

In an ac system with the proposed voltage and current levels for NEPTUNE, even a rudimentary switch or fuse is adequate. However, because it is difficult to interrupt dc, some special arrangement in the electronics is required for a dc switch. Usually, an oscillatory current is imposed on the dc, producing a zero, though other methods have been suggested. A number of schemes were described by Adamson and Hingorani [6], and by Kimbark [7]. None have made any impact on HVdc systems, which continue to use the rectifier to interrupt the current.

Further, dc systems have insulation problems that have no counterpart in ac systems. Long-term dc excitation causes breakdown (“treeing”) of solid insulation. Typically, the cable insulation has to be derated.

While dc is conventionally used on undersea telecommunication cables, it is worthwhile to consider an ac alternative. However, an ac system at ordinary power frequency can be ruled out. Both the shunt capacitance and the series inductance of a typical telecommunication cable would require compensation. At 60 Hz, even at only 5 kV, the shunt capacitance of a typical cable, 0.2 μF/km, would require 2 kVAr of compensation per km in order to reduce the charging current to a value below the ampacity of the cable. At an estimated \$5/VAr, this would nearly double the cable cost.

An alternative ac approach is to use a different frequency. If the frequency is decreased from the standard 60 Hz to 0.1 Hz, the charging current is reduced to a negligible value. The effect of series inductance is similarly reduced. Technically, the ac option appears viable at very low frequency (VLF). Much of the equipment required to implement VLF ac should be the same as for dc. However, the need for energy storage in the converter would add to the cost and complexity of a VLF ac system.

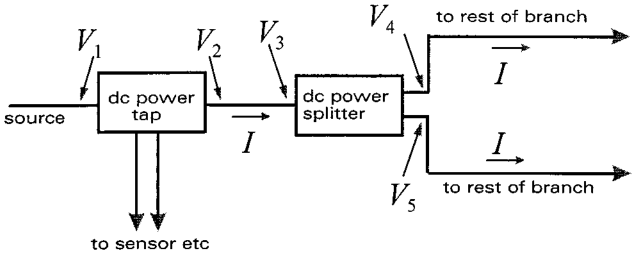


Fig. 2. Branching in a constant current system requires active control.

Thus, in terms of cost, the decision favors dc. A more detailed tradeoff study considering the capability, complexity, and lifetime cost of two alternatives could be done, and may change this conclusion, because it could take into account the possible extension of the cable lifetime. However, it is unlikely that the complexity of VLF ac would be justified unless a considerable increase in voltage were needed.

B. Series or Parallel?

A series connection of the sources and loads is usually used in underwater telecommunication cables to power in-line repeaters. The ocean is used for the return current path, so the cost of a return conductor is avoided. This feature can be retained whether the power system is series or parallel; a parallel scheme, however, requires more ground connections. There is no requirement to split the cable under the ocean in a telecommunications application. Because of this, the technology to create a branched power network using constant current has not been developed. Branching is feasible, but it only requires an incoming current to be regenerated twice (or more) at a lower voltage (Fig. 2). A dc/dc converter (Fig. 2) could be installed wherever a branch is needed in the network. It would have to be duplicated or re-connected if the power flow direction changed (for example, because of an outage in the system), but there seems to be no reason this could not be done.

In a constant current system, at a tap where an amount of power P is removed, the volt drop is given by $V_1 - V_2 = P/I$, provided the converter is 100% efficient and able to convert a constant input current into a constant output voltage. Note that neither MV terminal of the converter is grounded.

Because power is conserved at the branch splitter, $V_3 = V_4 + V_5$. The implication is that there is no efficiency benefit to branching. A parallel system gains efficiency if the loads are fed from different branches, because the same high voltage is applied to all branches. With a branch in a series configuration constrained to operate at reduced voltage, the efficiency is unaltered by the branching.

Another reason for preferring a parallel system is higher power capability. In Figs. 3–5, a system with asingle source and three loads, each demanding the same power, is assumed. A cable resistance of 1.5 Ω/km is assumed. The first load is separated from the source by 333 1/3 km, and the loads are 100 km apart. The cable resistance is 500 Ω to the first load, and 150 Ω between the next two loads. The shore power source is assumed to have maximum ratings of 10 kV and 10 A.

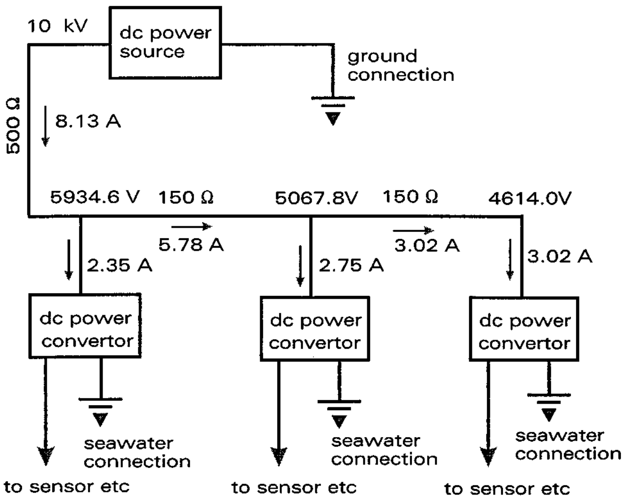


Fig. 3. Current and voltage values for maximum power in a parallel power system.

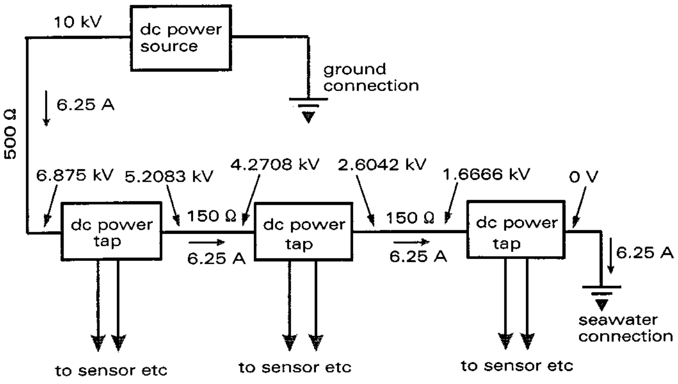


Fig. 4. Current and voltage values for maximum power in a series power system.

The loads are connected in parallel (Fig. 3) or in series (Fig. 4). In each case the load is increased to a maximum value. Figs. 3 and 4 indicate that the parallel scheme has an advantage over the "conventional" series circuit because it can deliver more power. For the series case, the source power is 62.5 kW. The connection manages to deliver 10.41 kW to each load. The parallel connection requires 82 kW at the source to deliver nearly 14 kW of useful power to each load. The efficiencies are 50%.

Although both systems operate at 50% efficiency when they are at maximum power, the efficiencies vary with power. Assuming that the series system current is adjusted to the current value that corresponds to maximum power (Fig. 4), the losses in the system are then constant, so that the efficiency is low at low delivered power. The parallel scheme (Fig. 3) has losses that increase with the load. The two schemes are compared in Fig. 5.

The higher efficiency translates to a lower electric bill, but more importantly, the higher power limit available from the parallel connection provides a greater science capability. A sufficiently high level of power might be viewed as enabling "intervention" science, as well as observation.

This example, although it is only one topology and one set of values, supports the conclusion that a parallel system is *always* capable of delivering more power. The series system constant current will always have more I^2R loss than a system where the current decreases (and returns via the ocean) at each junction box.

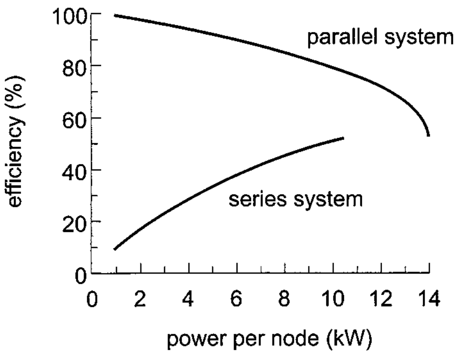


Fig. 5. Efficiency as a function of delivered power for the series and parallel schemes.

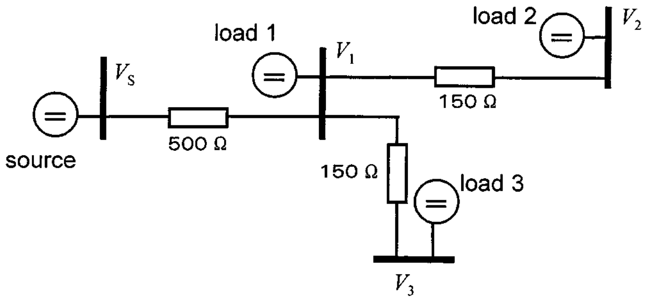


Fig. 6. One-line diagram of a branched power system.

Further, if the parallel or series systems were modified so that the 2nd and 3rd loads were fed on separate branches from the first load, the one-line diagram for the parallel scheme would be as shown in Fig. 6. The series scheme would differ in that a branching power supply would be needed after node 1 to supply the current for the two branches at reduced voltage.

Analysis of the systems represented by Fig. 6 shows that, for the parallel scheme, the power per node increases from 14 kW to over 15.5 kW. (The improvement is modest because most of the losses are still caused by the high resistance of the first line segment.) For the series scheme, the power per node remains at 10.4 kW.

The parallel scheme should not be construed to imply that the power system would be *operated* at nearly 14 kW per node, any more than it supports the idea that a system that is fed from one end only represents good design. The peak power a system could deliver is discussed next. First, maximum values for the voltage and current must be established.

C. Maximum Voltage

The maximum voltage that can be applied to a cable is limited by the likelihood of insulation breakdown. This, in turn, is limited by the electric field gradient at the inner conductor surface. The E-field in a coaxial cylinder geometry varies as the reciprocal of the radial distance. With realistic values for the cable dimensions, and considering fields inside the cable, a level of 10 kV could be used, and likely higher. Practically all long-distance telecommunication cables are rated for 10 kV; a few are rated higher. Although the electric field is moderately low at this level of voltage (4 kV/mm), experience shows that insulation life may be shortened by the long-term application of greater voltages unless ac is used.

D. Maximum Current

The current carrying capability (ampacity) of a submarine telecommunications cable is not part of its electrical specification; perhaps because there has never been a need to approach this limit in normal applications. Nevertheless, if NEPTUNE is to have a flexible power system, the upper bound on this parameter must be known.

Manufacturers' published data state that the typical submarine cable has a series resistance of less than 1.5 Ω/km. Assuming that the cable material (and hence, conductivity) is the same as for residential wiring, the nearest equivalent wire size is #6 AWG, which in free air has an ampacity (thermal limit) of 100 A, for example.

However, at 100 A, the voltage drop in 100 km of cable would be 15 kV, which may exceed the breakdown stress value of the cable insulation. Additionally, the thickenss of the required insulation may offset the superior thermal properties of seawater over air. Therefore, in practice, the current limit may be determined by the maximum voltage. In fact, the maximum power analysis provided in the following section limits the amount of current flowing through the proposed NEPTUNE system to about 10 A. As a result the required thermal dissipation should not approach the thermal rating of the insulation.

E. Maximum Power

While voltage and current limits are known by considering insulation lifetime and voltage drop, establishing a value for the maximum power that can be delivered by a network is more complex. An estimate of the maximum power must take into account both maximum current and maximum voltage, but may actually be determined by neither one of them. This observation is true whether the network is energized with dc or with ac: the maximum power capability is a function of the network. The equations are different, but the principles are the same.

Apart from constraints of maximum current and voltage, the maximum power question (whether ac or dc) is intimately connected with voltage stability in the network. Since all large power systems are ac, the extensive literature on the subject concerns only ac networks. (The website http://www.ee.iastate.edu/~venkatar/Biblio/biblio.html lists several hundred citations on voltage stability, e.g., [8], [9], and [10].)

The undersea observatory network is likely to be dc. Since the question of maximum power has been addressed extensively only for ac networks, we take an ac system analysis as the starting point.

In an ac network of the simple configuration shown in Fig. 7, the steady-state power across a line is given by the equation

$$P = \frac{V_1 V_2}{X_L} \sin\delta$$

where P is the received power, V_1 and V_2 are the voltages at the ends of the line, and δ is the angle between them. The nonlinearity of the sin term implies that there is a maximum power, reached when $\delta = 90°$. Since most power systems are operated with automatic controls that maintain the voltage at any bus close to its nominal value (i.e., 1 per unit; pu), it follows that the maximum power is established by the line series inductance. Once a line design is fixed, there is a maximum power that it can transmit. If the voltages are at 1 pu, and the series reactance is 1 pu, the maximum power is 1 pu at $\delta = 90°$.

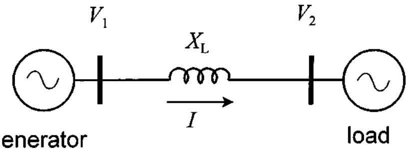


Fig. 7. Radial ac power system.

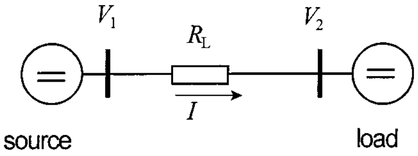
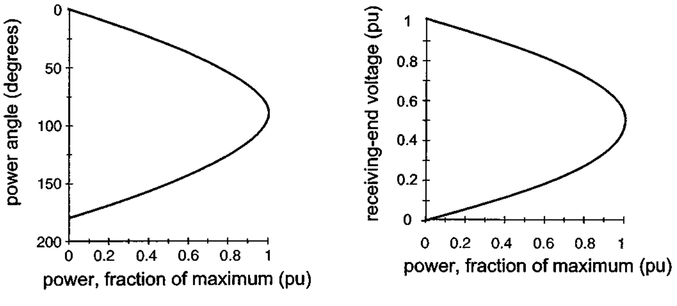


Fig. 8. Radial dc power system.



ac system power/angle curve **dc system power/voltage curve**

Fig. 9. Power system nonlinearities.

A similar nonlinearity exists in a dc power system. For dc, however, resistance is important (Fig. 8). Unlike the ac case, the voltages are not constant.

In a dc power system

$$P = V_2 I = V_2 \left(\frac{V_1 - V_2}{R_L} \right).$$

If V_1 is fixed at 1 pu, R_L is 1 pu, and V_2 is allowed to vary as the power changes, the voltage drop in the series resistance causes the power at the receiving end to reach a maximum value of (1/4)V_1^2/R_L when $V_2 = V_1/2$. This is the condition known as "matched" in RF and audio engineering. While the nonlinearities of the ac and dc cases are based on different causes, they are not different in overall appearance (Fig. 9).

The curves in Fig. 9, however, have been normalized based on maximum power, which is always lower in the dc system. This difference arises because the dc system is modeled as lossy and the ac system is not. With the values used above (i.e., all fixed parameters set to 1 pu), the maximum power in the dc system is 0.25 pu, compared to 1 pu for the ac system. In the dc case, the load voltage is half the source voltage, the resistance seen by the source is 2 pu, and the current is therefore 0.5 pu. Both the load voltage and current are half their ac values.

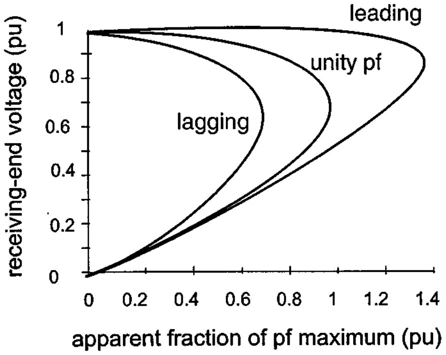


Fig. 10. Power-system power/voltage curves.

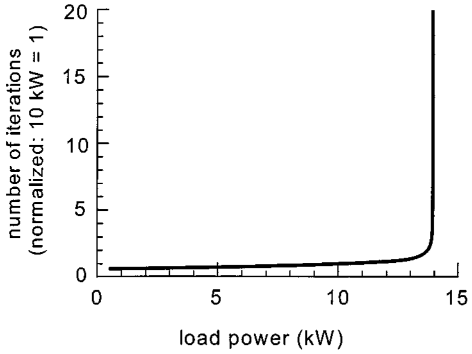


Fig. 11. Number of iterations needed to solve the system of Fig. 3.

This factor of 4 difference is a result of the choice of values and the custom of neglecting resistance in ac power flows. The point here is not the difference in magnitude, but the similarity of shape of the two curves. While a change in power in one case causes a change in angle, and in the other, a change in voltage, the effect is qualitatively similar.

In the upper half of the curves, load voltage decreases as the power increases. After this the slope reverses. In each case, the point of infinite slope represents a point of maximum power. If the load tries to demand more power, it cannot be delivered and unstable operation results.

For an ac power system, this is *voltage instability.* It is a very real effect. It first came to widespread attention when most of France was blacked out on December 19, 1978 [11], [12]. In a practical power system, the load does not consist of a resistor, it includes such things as motors, lights, battery chargers, and refrigerators. The aggregate load is therefore better represented by a constant power demand (about which there is more below) and a reactive power consumption. The load may have a leading power factor or a lagging power factor. The power factor may change as a function of time, with some systems being capacitive at light load and inductive at heavy load times because of support from the capacitance of the delivery system itself.

A simplified solution showing the effect of load power factor can be drawn (Fig. 10). The power on the abscissa is the apparent power, $S = P + jQ$. With a leading power factor load, the total power can exceed the value for a resistive load, because the capacitance compensates for the inductance of the delivery system. Leading power factor loads tend to support voltage, and inductive loads tend to depress voltage.

Because the peak power value with a lagging power factor is less than with a leading power factor, the lower power limit is associated with a depressed system voltage. Voltage support and adequate reactive power supply are crucial to maintaining stability, even though, in the end, it is a power problem that causes the limit to be exceeded. The symptoms of the approach of this kind of instability are a greater decrease in voltage than would be expected for a given increase in load. At the same time, the voltages around the system are hard to maintain. It is because of this that the name voltage instability is appropriate.

Of course, no real power system is as simple as those shown. Power systems, even those planned for undersea observatories, are complex networks with multiple interconnections for reliability purposes. The problem is, then, to determine the actual value of the maximum power transfer, bearing in mind that the load will not be the same at all the nodes, nor will it be time-invariant. In practice, these calculations are done in a continuing, near-real-time mode.

There are two approaches. One is to run the power flow calculation (i.e., a nonlinear, iterative solution to Kirchoffs's current and voltage laws) based on system measurements, and pay attention to the voltage profile in the system. A difficulty with this is that the power flow calculation near maximum power becomes ill-conditioned. This means that convergence becomes slow. An alternative method recognizes that the instability is due to a bifurcation, corresponding to a zero Jacobian eigenvalue. Methods have been developed that use system measurements to calculate the Jacobian eigenvalue in near real time. Maximum power corresponds to the minimum singular value of the Jacobian eigenvalue [13], [14].

Whichever approach is taken, it will only be important at times of high load. A problem of equal importance is the determination of instability supplying load after a contingency, when a load can become "high" following an outage. For example, the proposed NEPTUNE system is planned to be capable of delivering 2 kW to all nodes at the same time. A power flow has shown that the system can in fact deliver 6.7 kW to all nodes at the same time, although this may be near the voltage stability limit. At such a load, there are two locations in the network where the power flow is nearly zero. Losing either of these lines would not affect the system. The loss of any *other* line, however, may well take the system beyond its safe operating region. Contingency analyses could identify such a situation, and remedial action could be taken.

To return to the three-load example, a parallel delivery system is better than a series one if the practical level of power is higher. Because the peak power capability for the system is almost 14 kW, at least 10 kW can be delivered by the parallel scheme (i.e., ~70% of maximum, with a 30% safety margin). In fact, rapid convergence of the power flow software is obtained at 13 kW, indicating that operation at this level should be safe. This is more than even the *peak* power in the series scheme.

The convergence of the power flow is shown in Fig. 11, where the number of iterations is plotted as a function of power. There is no problem at a load level of 12 or 13 kW. Above this power level, however, the number of iterations required rises rapidly. No solution is found at 14 kW.

While convergence of the software and stability of the system are not exactly equivalent, they are strongly related. It is on the basis of the higher power available that a parallel system was chosen for NEPTUNE and is generally preferred.

As the analysis shows, the maximum power that can be transported across the network is limited by voltage instability. In the case of NEPTUNE, the current in most of the network is less than 10 A when voltage stability becomes dominant, so neither voltage drop nor temperature rise are at issue.

F. Dynamic Stability

Switching mode regulators are routinely used at power levels from milliwatts and up because of their high efficiency. In a cabled observatory, this efficiency translates into simplified cooling in a pressure case, and possibly more available power. With a well-designed switching regulator, the input voltage can vary over a wide range (say, 2 : 1) without affecting the output.

A dc/dc converter that includes such a regulator presents a constant load to the source because all load is on the regulated side of the converter. If the input voltage drops, the converter compensates and the input current increases. This means that the source will have a negative incremental resistance, and the system may become unstable. While the input resistance R_{in} is $V_{\text{in}}/I_{\text{in}}$, the incremental value R_{incr} is given by

$$\begin{aligned} R_{\text{incr}} &= \frac{dV_{\text{in}}}{dI_{\text{in}}} = \frac{d}{dI_{\text{in}}}\frac{P}{I_{\text{in}}} = -\frac{P}{I_{\text{in}}^2} = -\frac{V_{\text{in}}}{I_{\text{in}}} \\ &= -k^2\frac{V_{\text{out}}}{I_{\text{out}}} = -k^2 R_{\text{load}} \end{aligned}$$

where k is the voltage ratio $V_{\text{in}}/V_{\text{out}}$ of the converter, and the load resistance is R_{load}. Thus, the incremental input resistance varies as the square of the voltage ratio (as in a transformer), but is negative.

Negative incremental resistance is sometimes experienced in the design of RF integrated circuits. The solution is to put a resistor in parallel with the input to the IC or in series with the output (as appropriate) to avoid oscillation. In RF work, the power loss associated with this technique is acceptable. In a power system, it is not. Fortunately, an alternative method based on input filter design is available.

Because the negative incremental resistance is effective below the crossover frequency of the loop gain of the control circuit of the converter, the input filter will certainly oscillate when its resonant frequency falls below the crossover frequency. Hence, the input filter should be damped to ensure that around its resonant frequency the negative input impedance of the converter is compensated by the damping resistance of the damping network [15].

To demonstrate the approach, the simple 1-source 3-load system of Fig. 3 was modeled in Pspice. The cable was modeled as 25-km L-sections, with a series inductance of 1 mH/km, a series resistance of 1 Ω/km, and shunt capacitance of 0.2 μF/km, and the loads were set at 10 kW (Fig. 12). Because the cable itself is well damped and does not pose any source of instability for the converter, the results and conclusions presented below are not dependent on the precise model or parameters of the cable.

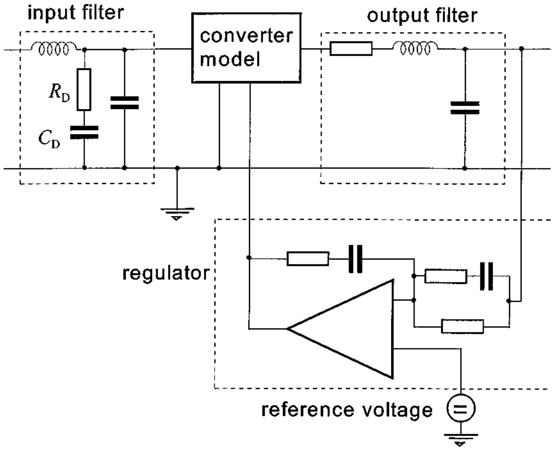


Fig. 12. Circuit model used in Pspice simulation.

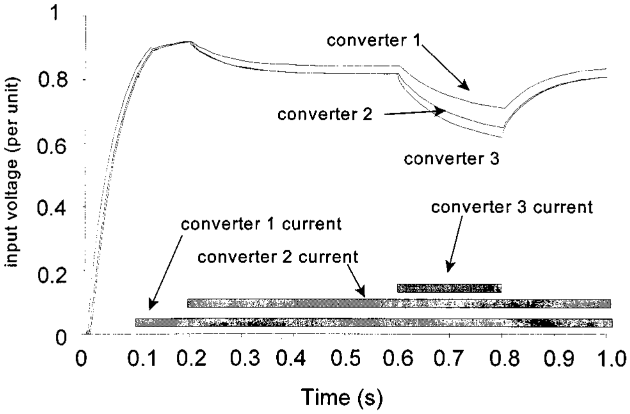


Fig. 13. Results of Pspice simulation.

Central to the model is the converter model. This is a well-tested simulation of a switching converter [16]. The particular version used here represents the response of the system to changes in input and output as smooth functions. This allows fast simulation, avoiding the need to model the switching process itself. Control for the regulation action of the converter is obtained by a high gain amplifier that compares the output voltage with a reference voltage. (Turning the reference voltage off serves to turn the converter off in this model.) The input filter is nondissipative at steady state.

Three of these converters were embedded in an arrangement like that shown in Fig. 3 to simulate the entire system. Fig. 13 shows one representative result. First, the source voltage is applied. One hundred milliseconds later, converter 1 load (10 kW) turns on, and 100 ms after that converter 2 load is applied. The transitions from one operating state to another are properly damped. At 600 ms, a 10-kW load is applied to converter 3 with a duration of 200 ms. The state transitions are stable.

In other simulations with this model, the loads were left steady long enough for the system to stabilize, i.e., 1 s. The voltage profile on the line was the same as calculated by steady-state simulations.

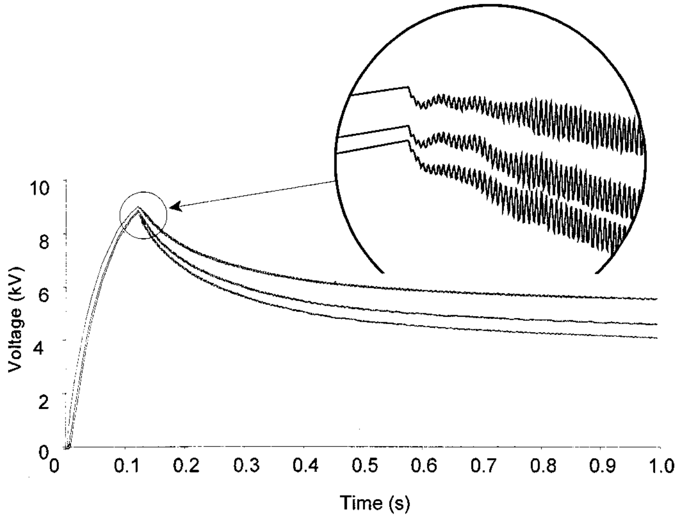


Fig. 14. Results of Pspice simulation, damping components omitted.

Users of ready-made dc–dc converters may use the hardware without considering the damping effect of the RC network in the input filter (R_D and C_D in Fig. 11). This omission could have serious consequences. To demonstrate this, the simulation was run without the damping components present (Fig. 14).

The buildup of oscillations following the application of the load is clear (in this case, all the loads turned on simultaneously). As the input voltage swings (here, about 7 kHz), the converters attempt to regulate against the growing input oscillations, requiring operation at a wider and wider range of duty cycles. Eventually, the duty cycle in the trough of the input voltage becomes unity, the feedback can no longer regulate the output, and it saturates. Before 2 s has elapsed, the system has crashed (not shown).

The input filter serves to keep the switching noise out of the MV side of the system. Further, any high-frequency transients created in the MV network (e.g., by switching or by faults) will be removed by this input filter before they reach the converter. However, a crucial additional function of the filter is to stabilize the system at frequencies up to and above the gain-crossover frequency of the regulator. Omission of the damping components leads to instability.

For both an observatory using existing repeaters and constrained to a particular current, and for a new observatory with no such constraints, appropriate filter design will allow the science load on the system to be maximized.

III. CONCLUSION

By adapting terrestrial utility practice to an undersea application, a fault-tolerant power delivery system can be built. The difference from utility power delivery approaches is the use of direct current, which is justified by cost. Higher voltage, and therefore higher power, may be possible with VLF ac, but is not needed to meet NEPTUNE's proposed requirements. Therefore, we conclude: 1) a parallel scheme, as used in utility systems, is capable of delivering more power than a series scheme, and branching is easier to implement; 2) maximum power transmission capability is limited by line parameters and load distribution, rather than the power source limits; and 3) possible instability caused by regulator action in the constant-voltage power supplies is readily avoided by proper choice of damping components in the input filter.

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