Parallel Power for Undersea Application: The Basic Considerations

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Abstract

Power systems for undersea observatories are required to deliver high power with good reliability. For the proposed NEPTUNE observatory, the authors have developed a power scheme that combines ideas from terrestrial power systems and switching power supplies with experience from undersea cable systems. The system is based on a parallel network. This design can be applied to other undersea schemes, where it can allow longer cables with less copper. Key performance factors are explored in this paper.

Introduction

Scientific interest is growing in the application of undersea cabled observatories (see special issues of *Oceanography*, Brink, 2000a,b). The Long-term Eco-system Observatory (LEO-15) is an example, with two nodes in 15 m of water 7 km off the New Jersey coast (Grassle *et al.*, 1998; Glenn *et al.*, 2000). It supports a variety of science instrumentation including a winched CTD, video, and autonomous undersea vehicles (AUVs). LEO-15 makes it clear that power is required not just for electronics but also for motion, light, and heat transfer.

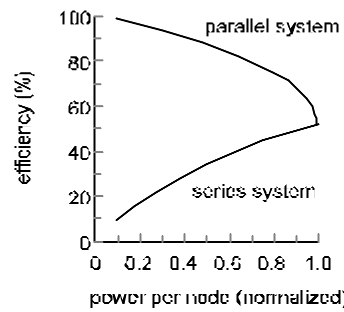
A parallel power scheme has been devised for the proposed NEPTUNE observatory (Delaney *et al.*, 2000). However, while this high-power application drove the design, it is clear that at the lower power levels needed for telecommunication repeaters, the improved efficiency of power delivery by a parallel scheme would allow either less copper to be used in a given cable route, or an existing cable design to be used on a longer route.

Parallel Power

A series connection of the sources and loads is conventionally used in underwater telecommunication cables to power in-line repeaters. There is, however, a reason for considering a parallel system: higher power capability.

Interestingly, although both series and parallel systems are at 50% efficiency when they are at maximum power, the efficiencies vary quite differently with power. Assume that there is a series system whose current is adjusted to the value that corresponds to maximum power, and a parallel system whose voltage is at the cable maximum. If the load in the series system changes, the losses are still constant. The result is that the efficiency is low at low delivered power. The parallel scheme, on the other hand, has losses that increase with the load. The efficiencies of the two schemes are compared, for normalized system parameters, in Figure 1.

Figure 1: Efficiency as a function of delivered power for series and parallel schemes



More importantly, in addition to being more efficient, the parallel system can deliver much more power. Even assuming that in the series system the converter is 100% efficient, which is typically far from true, the parallel system is more capable. For the proposed NEPTUNE network, a series system is estimated to be capable of delivering only 20 kW to the entire system, whereas a parallel scheme has been shown capable of delivering over 6 kW to each of the 30 nodes. While the exact power ratio may depend on the details of the system parameters, in general, a factor of over 10 may be realistic. The higher efficiency implies a lower electric bill, but more importantly for an observatory such as NEPTUNE the higher power limit that results from the use of the parallel connection implies a greater science capability. For telecommunication applications, it translates into greater distances with less copper.

Maximum Power

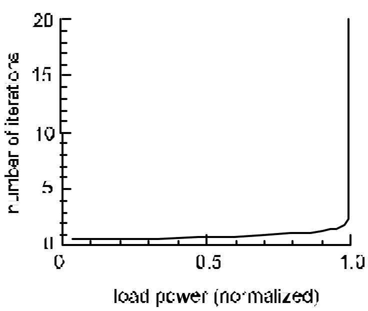
While the voltage and current limits can be set simply by consideration of insulation lifetime and perhaps vo1tage drop, establishing a value for the maximum power that can be delivered by a network is more complex. Although undersea cables tend to be dc, the theory of maximum power has been addressed extensively only for ac networks. Since December 1978, when a good deal of the French power system failed

(Journées, 1980; Barbier and Barret, 1980), there have been many papers written on the subject. (The website http://www.ee.iastate.edu/~venkatar/Biblio/biblio.html lists several hundred.). Therefore, ac system analysis is our starting point.

Maximum power transfer manifests itself as a kind of instability is known as *voltage instability*. 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. The problem is to determine the actual value of the maximum power transfer, bearing in mind that in the general case the load will not be the same at all the nodes, nor will it be time-invariant.

There are two approaches. The more obvious is to run the load flow calculation, based on system measurements, and pay attention to the voltage profile in the system. A difficulty with this is that the load 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 in near real time. Maximum power corresponds to the minimum singular value of the Jacobian (Begović and Phadke, 1989;Van Cutsem, 1995). The convergence of a load flow is shown in Figure 2, where the number of iterations is plotted as a function of power. There is no hint of a problem at a load level only 5% below peak power. Above this power level, the number of iterations required rises rapidly. No solution is found at peak power.

Figure 2: Number of iterations needed to solve the load flow equations of a power system



While convergence of the software and stability of the system are not exactly equivalent, they are strongly related. Provided power transfer is kept at or below about 95% of the theoretical peak value, stable operation should result.

Dynamic Stability

A dc/dc converter that includes a regulator presents essentially a constant load to the source, since 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 see a negative incremental resistance, and the system may go unstable.

Negative incremental resistance is sometimes experienced in the design of RF integrated circuits. The solution there 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. It is fortunate that an alternative method, based on input filter design, is available.

Since the negative incremental resistance effect is a low-frequency one only (due to the regulation action), Middlebrook (1976) showed that any oscillations that occurred were likely to be at the crossover frequency of the input filter, where the filter impedance increased. He demonstrated that by choosing the filter components properly, the potential instability could be eliminated. Further, the filter design was not dissipative in the steady-state.

To demonstrate the approach, a simple 1-source 3-load system was modeled in Pspice. Figure 3 shows one representative result.

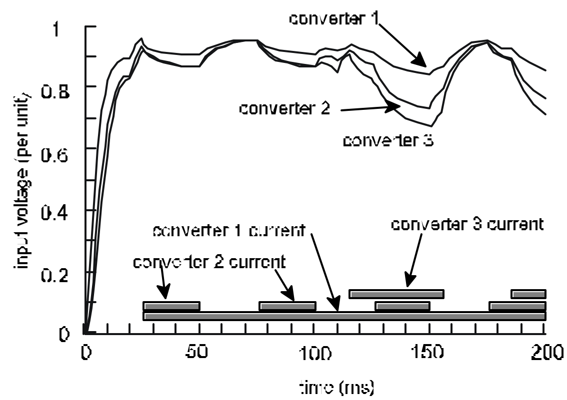


Figure 3: Results of Pspice simulation

First, the source voltage is applied. 10 ms later converters 1 and 2 turn on, and at 25 ms the loads are applied. Converter 1 has a steady load, and converter 2 a pulsed load. The transitions from one operating state to another can be seen to be properly damped. At 125 ms, converter 3 is turned on, with a pulsed load. The state transitions can be seen to be quite stable, as expected.

In other simulations with this model, the loads were left steady long enough for the system to stabilize, ie 100 ms or so. The voltage profile on the line was then the same as the one calculated by the steady-state simulations.

It may be that users of ready-made dc-dc converters might be tempted to use the hardware without regard to the damping effect of the R-C network mandated by

Middlebrook's work to be included in the input filter. Such an omission could have serious consequences. To demonstrate this, the simulation was run without the damping components present. The results are shown in Figure 4.

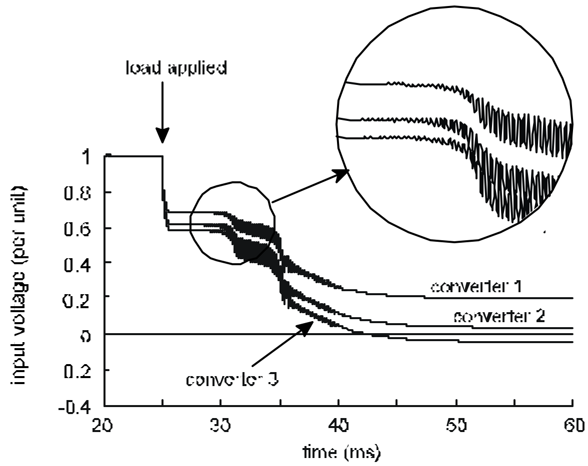


Figure 4: Results of Pspice simulation, damping components omitted

The buildup of oscillations following the application of the load is clear. As the input voltage swings (here at around 8 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. The system has crashed.

The input filter serves to keep switching noise out of the MV side of the system. Further, any high-frequency transients created in the MV network (for example 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.

Conclusions

A parallel power delivery system has much to offer compared to the conventional series approach.

- A parallel scheme is capable of delivering more power than a series scheme
- Branching is easier to implement
- 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.

These results suggest that parallel power should receive consideration not only for science observatories, but also for long-distance telecommunications.

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