Powering Cabled Ocean-Bottom Observatories

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***Abstract*—A critical and potentially difficult problem for ocean-bottom observatories is the electrical power sub-system. While huge effort and expense has gone into development of land power grids and ocean communication cable power, the characteristics of ocean-bottom observatories require different strategies. Ocean-bottom observatories terminate on the ocean floor where large variable loads are installed, whereas commercial ocean-bottom cables terminate on land and normally have relatively fixed loads. Design considerations such as whether to use a constant current or constant voltage source, choice of voltage and current levels and cable capacitance and impedance are considered. Ocean-bottom observatory science requirements in the future will demand multiple loads along the cable, cable branches, fault protection and redundancy. The realities of high cable capacitance and the negative dynamic impedance of switching power supplies require that rapid load changes either be anticipated or prevented. Without proper control, rapid changes in load can result in instability and collapse of the power system. The strategy suggested in this paper requires that each load point (or junction box where science experiments will be attached to the system) be "smart" enough to keep load variations within tolerance bounds.**

***Index Terms*—Marine technology, ocean bottom observatory, power system dynamic stability, power system modeling, power system transient stability.**

I. INTRODUCTION

A. Scope

RECENT interest in installing scientific observatories on the ocean floor presents many challenges in providing experiments with stable and reliable power. Observatories attached to buoys or to battery packs on the ocean floor do not have to deal with the complexities of powering very long cables from shore, but such observatories suffer from the need for periodic replacement of consumables. In this paper, we assume that the engineer is tasked with supplying power to cabled systems on the ocean floor with initial conditions that can include: 1) cable lengths of thousands of km; 2) loads that can change instantly by an order of magnitude or more with the addition or failure of experiments; 3) constraints emplaced by the characteristics of existing hardware; 4) cable branches and loops; and 5) the realities of cable and repeater costs. We discuss the impact of each of these conditions on the design of power systems for ocean-bottom observatories.

B. Cable Considerations

1) Using Existing Cables: We consider two scenarios: 1) where an existing coaxial cable is re-used after being removed from telecommunications service, and 2) where a new electro-optical cable is laid for observatory use. With the rapid proliferation of fiber-optic transoceanic cables, most of the transoceanic coaxial telephone cables have been or soon will be retired. While they are no longer competitive in the telecommunications market due to their limited bandwidth, they are adequate for a wide range of deep-ocean scientific experiments. In time, some of the early electro-optic cables will also be retired because of limited bandwidth.

2) Repeaters: Transoceanic communications cable systems use constant-current dc electrical power with sea-water returns that are usually powered from both ends of the cable with a virtual ground (0 V between the center conductor and seawater) near the center. Power is needed for repeaters in the cable that boost the signal power about every 10–100 km. Each repeater is a series load, dropping the voltage by a fixed amount. In addition, resistance of the cable drops the voltage by a fixed amount every kilometer. Each repeater requires a fixed current, but the voltage to seawater at any point can be allowed to vary over a wide range, such that the cable can operate with a power supply at only one end if necessary. Reuse of these cables for scientific use requires adapting the science system to the existing power system. This generally means converting from fixed-current in the cable to fixed-voltages available to experiments and deploying a seawater return at the experiment site. This is the situation with the Hawaii-2 Observatory [1], now in operation half way between Hawaii and California and it will also be the case when the older electro-optical cables are de-commissioned. The constraints on the power system imposed by the constant-current repeaters must be fully addressed in order to avoid compromising the long-term reliability of the repeaters in the cable system. A cable 1000–mil long has a capacitance of nearly 200 μF. Any sudden changes in the voltage across the load at the end of the cable can produce large voltage drops and potentially damaging current stresses on the nearest repeaters. Since it is likely that individual loads in experiment packages will be turned on and off, some form of regulation is required to safely isolate these changes from the cable repeaters.

The constant-current scheme used in most repeatered systems imposes serious constraints on the system design which include the following. 1) A constant-current system with standard regulated switching converters is unstable. The stability criteria will be discussed later. Shunt regulators (with their added system complexity and cost and the added power loss) are required with a constant-current system. 2) Power distribution becomes very problematic if any branching is required. To avoid or minimize these problems, a new cable system should probably use a constant-voltage supply scheme. The design considerations for a stable and reliable voltage supply will be evaluated later in this paper.

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II. BASICS

Before detailed discussion of overall system design, we review some basic concepts and principles important for understanding the constraints involved.

A. Power Delivery and DC–DC Converters

1) DC–DC Power Supply Characteristics: One of the realities of ocean-bottom observatories will be the use of constant-power dc–dc converters to supply electrical power to experiments. These regulated converters supply a constant voltage to the load, adjusting the primary current as required by the load. They will draw the required power from the source regardless of the current or voltage supplied. The fact that they are "high efficiency" implies that only a small amount of power is lost in the conversion. The characteristics of these power supplies are profoundly different from resistive loads in that they present a negative dynamic impedance at their input. This means that the input to the converter appears as a constant-power load rather than a constant-resistance load and the input current actually decreases as the input voltage increases. A constant-power input characteristic is defined by: $P_{\mathrm{in}} = V_{\mathrm{in}} \times I_{\mathrm{in}}$ or $I_{\mathrm{in}} = P_{\mathrm{in}}/V_{\mathrm{in}}$, where V_{in} is the voltage at the input to the dc–dc converter and I_{in} is the current at the input. A constant-power curve on a plot of cable current versus voltage at the input to a dc–dc converter is hyperbolic when the converter is in regulation; the voltage varies inversely with the current along a constant-power curve with a slope of $-I_{\mathrm{in}}/V_{\mathrm{in}}, = -P_{\mathrm{in}}/V_{\mathrm{in}}^2$. In contrast, a resistive load would have a positive slope of 1/R with an intercept at zero. In practical dc–dc converters, the unit goes out-of-regulation at low voltages resulting in the load power curves shown in Fig. 1 for a hypothetical case.

2) Cable Load Lines: The straight lines in Fig. 1 are cable load lines. A load line represents all of the combinations of voltage and current available at the load. For a constant-voltage source, the load line shown as the upper thick line has the source voltage as the x-intercept (2 kV in this case) and the slope is the negative inverse of the sum of the series resistances along the whole cable. The load line for a constant-current source (shown as the heavy dotted line) will be horizontal at the appropriate current. The family of power curves represents the input to the dc–dc converter for various power demands.

3) Operating Point: An operating point is defined as the voltage and current where the system operates. For the situation shown in Fig. 1(a) by the constant-voltage case, operating points exist at intersections of the cable load line and the power curve, but not all of these intersections are stable or useable. Although operating points above 50% of the supply voltage are stable [open circles in Fig. 1(a)], the shift in the operating point for a given shift in power demand is magnified as 50% of the supply voltage is approached. As a rule of thumb, operating points above 70% or 75% of the supply voltage provide a comfortable stability margin in many cases. Operating points to the right of the peak of the power curve but below the 50% point are inherently unstable (black circles). For the constant-current case, all operating points to the right of the peak of the power curve are unstable. Operating points to the left of the peak of the power curve represent a converter that is out-of-regulation and not delivering proper power to the load (x'd circles). While these points are technically "stable" they are useless. This is the "collapsed supply" condition.

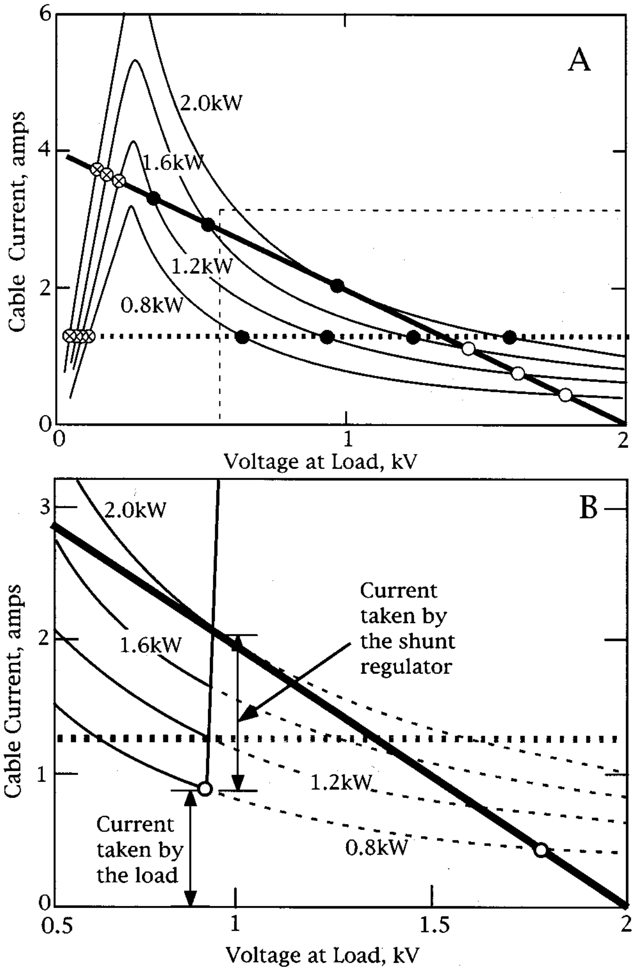

Fig. 1. DC–DC converter operation for a simple hypothetical observatory cable system. Curved lines show power curves for various load demands on a dc–dc converter. A load line for a 2000-V constant-voltage supply is shown as the solid thick line and a load line for a 1.25-A constant-current supply is shown as a horizontal dashed line. Stable operating points are shown as small open circles. Unstable operating points are shown as black circles and collapse-condition operating points are x'd circles. (b) is the expansion of the boxed area in the upper figure (a) modified by a shunt regulator at ∼ 1000 V. A stable operating point for a 0.8-kW load (circle) is shown. Without the regulator, the operating point would be near 1800 V. Part of the current is dissipated in the shunt regulator and part by the load as shown.

4) Shunt Regulators: Unstable operating points can be stabilized by introducing a shunt regulator at the expense of some wasted power. A shunt regulator monitors and regulates the voltage across the load by shunting current around the load to keep the total cable current at that point constant. The regulator makes the power curve appear almost vertical (positive slope) at the regulated voltage. The difference between the current delivered by the cable and the current drawn by the actual dc–dc converter is the shunt regulator current [Fig. 1(b)].

Stable operating points for the constant-power curve shown in Fig. 1(a) exist only for loads that are less than 2 kW and are on the right half of the figure. In the case of a constant-current power source (dashed line), the system in Fig. 1(a) is never stable (except out-of-regulation) when regulated dc–dc converters are used, because if the voltage at the input to a dc–dc converter drops for any reason, the converter will attempt to draw more current to keep power constant. Since the current cannot increase, the input voltage will be dragged down even farther, leading to a collapse of the system to the low-voltage state. Since all repeatered telecommunications cables operate on constant-current supplies, negative-impedance dc–dc converters must be isolated from the main power system. Note that all operating points are stable if the load is resistive, since the load curve has a positive slope.

5) Power Transfer: If transmitting power to the load were the only consideration, there might be some incentive to use the "maximum power-transfer theorem" [Fig. 2(a)] which states that for a given source voltage, maximum power transfer occurs when the load resistance is equal to the cable resistance. There are three arguments against its use; first, the power delivery efficiency is only 50%, requiring high voltage and power ratings for the shore supply. Efficiency can be increased by using a lower current and higher voltage. Second, the theorem applies only to a purely resistive load, not to regulated dc–dc converters. A resistive load would be represented in Fig. 1 by a line going through the origin with a positive slope, rather than by a constant-power curve. The third problem, stability, is discussed below.

6) Stability: If dc–dc converter inputs are connected directly to a cable, the power system becomes unstable when the voltage at the converter input reaches 50% of the source voltage. Although the 50% point is where the maximum power can be extracted from the cable [Fig. 2(a)], this voltage and lower voltages are unstable and the converter can no longer draw the required power from the cable. In Fig. 2(b) the power transfer curve is re-plotted to emphasize the fact that the rate of change of the input voltage increases rapidly as maximum power is approached. A small change in load when the system is operating near maximum power will produce a large change in voltage at the input to the dc–dc converter. To allow for normal startup surges and load fluctuations the power system designer must allow a comfortable margin to avoid the area where the voltage fluctuations become precipitous. Since some loads may have turn-on transients several times higher than quiescent demand, the danger of an unanticipated system collapse is real. Operating at a maximum 25% voltage drop from the source may be adequate for most systems, but careful consideration should be given to load transients before deciding on reasonable limits. Similarly, a shunt regulator must draw more current than the instantaneous surge current. A practical approach to ensuring stability is to temporarily boost the shore voltage in anticipation of a load increment in order to provide a safe current reserve during turn-on.

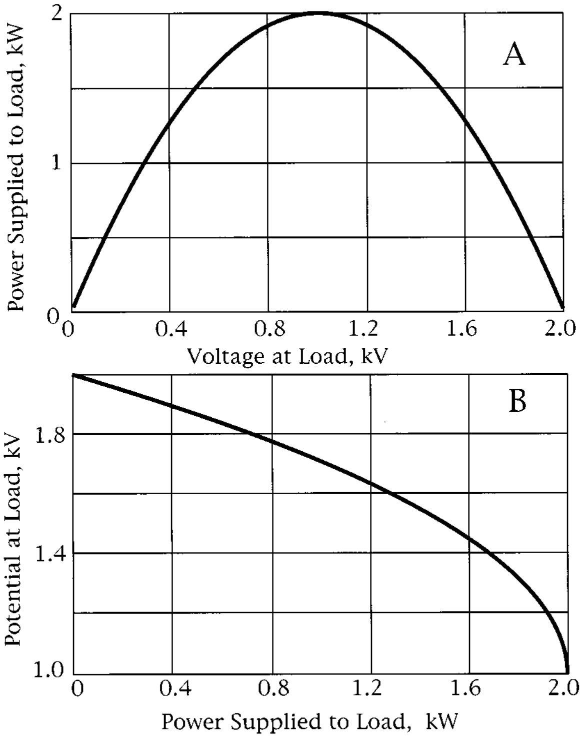

Fig. 2. (a) Power transfer to a load on a 500 Ω cable with a 2-kV shore supply. At 1 kV, the load draws 2 A and the maximum 2 kW, but this condition (and points to the left) are unstable when using regulated dc–dc converters. (Values of supply voltage and cable resistance are arbitrary.) (b) Voltage drop versus load power. Replotting Fig. 2(a) in this way emphasizes how the load voltage drops with increased power demand leading to collapse, should the voltage drop to 50% of the source voltage.

B. DC–DC Converter Characteristics

There is a strong incentive to use commercially available high-reliability power converters rather than custom-built units at locations where power is to be drawn from the cable. The reliability provided by thousands (or millions) of hours of testing and field experience on commercial converters cannot be matched in custom-built converters. However, the characteristics of off-the-shelf dc–dc power supplies place particularly strong constraints on ocean-bottom observatory power systems [2] and the system designer must recognize that most users are likely to incorporate them in their experiments. Power dissipation, voltage and current transients and varying loads all endanger the reliability of a converter. The disadvantage of commercially available converters is their relatively low input voltage rating of less than 400 V. Recommended conservative operation at 300–350 V may severely limit the available power. This leads to two choices: 1) design and test a high-input voltage converter or 2) devise a method for stacking high-reliability converters in series. Option 1) should not be taken lightly since semiconductors are intrinsically low-voltage devices. The limited availability and reliability of high-voltage semiconductors has restricted the development of higher voltage converters. Option 2) leads to the *absolute* requirement for shunt regulators to achieve a stable configuration if constant-power (regulated) converters are used.

One might assume that it should be possible in principle to modify the negative dynamic impedance input of a converter by feedback to stabilize the system. It should be noted, however, that if the input characteristics are modified substantially from a classical constant-power curve, the supply will no longer qualify as "high efficiency". The input characteristic curve cannot go below the constant-power curve at any point since that would represent greater than 100% efficiency. If it strays too far above the constant-power curve it represents poor efficiency. The general shape of the curve must therefore remain fairly close to the constant-power curve. This implies that the impedance remains negative. In actual practice, the input curve will be somewhat above the ideal curve due to converter losses and it will deviate somewhat because the converter losses are not constant over the input range. In general an "ideal" constant-power curve (with some nominal efficiency figure factored in) will suffice for initial stability modeling. Deviations from constant power are generally small and do not affect stability considerations.

C. Solutions to Instability

Two possible solutions to the instability problem are discussed: 1) never allowing the voltage to drop below 75% of the source voltage ("unregulated" case), and 2) the use of shunt regulators. In the first solution, the system is monitored and controlled from shore with changes in load carefully controlled to insure that no part of the array approaches instability. With multiple junction boxes and branches, this could be a formidable problem and a sudden short circuit or unanticipated load could cause instability and collapse of the power system. The situation could be made tolerable with programmable circuit breakers at each load point. Regulation is desirable in multiple-node systems with dynamic loads where it would largely eliminate interactions between nodes.

1) Unregulated Systems: A preferred approach for constant-voltage systems might be to design for operation in the safe region (where voltage drop in the cable is less than 25%). This would eliminate the need for the shunt regulators, with their added cost, power dissipation and system complexity. This is a very reasonable design goal, since even at the relatively safe level of 25% drop in the cable, 75% of the theoretical "maximum" power is available at the load. This is the solution used in the LEO-15 Observatory [7].

a) Input voltage limits: Operation of dc–dc converters directly from a high-voltage source poses other problems. Unfortunately there are practical limits to the input voltage of a single dc–dc converter. Semiconductors are intrinsically low voltage devices and, due to their small physical dimensions, the voltage stresses tend to be very high. High temperature and voltage gradients can cause the doping materials and impurities in the semiconductor to drift and degrade the high-voltage rating over time until the part fails. The industry consensus seems to be that 300–400 V (using $1000 +$ V rated semiconductors) is a comfortable limit for high-reliability operation. Truly high-voltage-rated semiconductors are physically large junction devices rated for many tens or hundreds of kilowatts of industrial power. Because of higher junction capacitances, these are generally much slower switching (small dc–dc converters operate at hundreds of kHz to over 1 MHz) leading to larger transformers and much higher core and switching losses. This can drastically reduce converter efficiency if a 50 kW device is operated at 500 W (1% of its rating).

In the figures in this paper, the "high-voltage" converters are assumed to be stacks of lower-voltage regulated converters to raise the voltage rating, like those used in the Hawaii-2 Observatory. Higher voltage and lower current minimizes the losses in the cable and makes it possible to deliver much higher power to the load.

2) Shunt Regulator: A second solution to this problem is to draw constant and stable power from the cable and dissipate excess power not delivered to the load in a shunt regulator. A shunt regulator generates a constant voltage at its output by shunting a fraction of the power available, reducing the dynamic impedance from very high (constant current or high cable resistance) at the input to relatively low (constant-voltage), as required by most practical loads. The regulator changes the cable load power curve from constant-power to a positive nearly-vertical slope at the voltage of the regulator as shown in Fig. 1(b). In this example, the shunt regulator limits the voltage at the load to about 1000 V. As the load increases, the power dissipated in the shunt regulator decreases. Using a shunt regulator, science loads can be changed without changing the current or voltage in the cable. Without a shunt regulator, the operating point for the 0.8 kW constant-source voltage case shown in Fig. 1(b) would be about 1800 V at a current of about 0.4 A (shown by the circle). If the load increased to 1.6 kW the cable voltage at the load would decrease to about 1400 V and current would increase to over 1.A. This change would affect all other operating points and repeaters on the cable.

b) Advantages of shunt regulators: The use of a shunt regulator has several other advantages; 1) it allows stable operation of dc–dc converters with constant-current sources; 2) it allows stable operation below 50% of the source voltage for constant-voltage sources; 3) it allows more power to be delivered to the observatory in constant-voltage systems and 4) it allows operation of dc–dc converters at lower input voltages. The shunt regulator provides a stable operating range between the power curve and the load line, but the operating point must never reach the load line or the system will collapse in the constant-current case, or if the voltage is half or less than the source voltage in the constant-voltage-source case. In the case shown in Fig. 1(b), the 1.2-A constant-current source with a 1.0 kV shunt regulator would be stable for loads of 0.8 kW or less, but would collapse before the load reached 1.2 kW.

Repeatered systems require careful attention to the effects of load changes on the constant-current required by the repeaters. Science loads can be safely added or removed from the system without severe transients by slowly changing the source voltage and the load taken by the shunt regulator. The safe rate-of-change of source voltage is dependent on the capacitance of the cable. The current at any point on the cable is

$$I_{\text{cable}} = I_{\text{const}} + C_c{}^{*}\frac{dv}{dt}$$

where C_c is the total cable capacitance of the cable and I_{const} is the specified constant operating current. This is a worst-case approximation since cable resistance will limit the current contribution of the distributed capacitance, most of which is far removed from the point in question. Some determination must be made as to the acceptable maximum percent momentary change in repeater current. This current change will define the maximum voltage rate of change. To keep instantaneous fluctuations to less that 10% would require $dv/dt < I_{\text{const}}/(10\ C)$ with the above approximation. For the Hawaii-2 cable, for example, this would amount to voltage change of less than 200 V/s. In constant-voltage systems the cable capacitance is an advantage since it contributes to a low-pass filter, minimizing transmission of instantaneous voltage changes.

c) Shunt regulator power dissipation and stability considerations: An important design compromise in the shunt regulator is deciding the total amount of excess power to dissipate in the regulator. The fraction of power dissipated is the safety margin for stability. In Fig. 1(b), the drop in current between the load line and the operating point on the power curve represents the shunt regulator current. The more excess power dissipation required, the larger the size and expense of the regulator. A large amount of heat dissipated in the regulator can also compromise the long-term reliability of the system. To fully protect the system, the shunt regulator should be able to dissipate all the power delivered at the operating point for short periods of time. Should a large load suddenly be disconnected, the load would need to be dissipated by the shunt regulator until the source could be adjusted by the shore control system.

d) Voltage limitation: There is another situation where regulation is desirable. If the designer wants to limit the load voltage in order to use standard high-reliability converters, the permissible shore voltage will be limited by the need to stay in the "25% voltage drop" range if regulation is not used. This requirement limits the cable current and load power. For a given cable resistance and load voltage, the only way to increase load power is to increase the shore voltage and cable current, eventually moving the load into the unstable region. With a shunt regulator, the cable can operate at any voltage up to its rated value and, while efficiency may be low because of high currents, far more power is available for the observatory loads. This was the design approach taken for the HUGO power system.

III. TWO EXAMPLES

A. General Introduction

We discuss the power systems of two existing observatories, HUGO, the Hawaii Undersea Geo-Observatory [3], using 47 km of commercial electro-optical cable and H2O, the Hawaii-2 Observatory, [1], [4], using a coaxial cable with repeaters. In both cases, DC current on a single conductor is used with a seawater return, and the observatory loads are at the ends of the cables. In the H2O case, the repeaters require that a constant-current power supply be used. In HUGO, we chose to use a constant-voltage supply.

B. The Hawaii Undersea Geo-Observatory (HUGO)

1) General Description: First we consider the case of a relatively short nonrepeatered fiber-optic cable. The power system design is constrained only by the maximum voltage and current specifications of the cable. A 47 km, 36 Ω SL-Light cable was donated by AT&T (now TYCO Submarine Systems International) to connect the shore station to the observatory. A design goal was to provide as much power as possible to a junction box at the end of the cable, which would in turn supply power to several multiplexing nodes where experiments could be connected. This "spider" design is appropriate for regions where the observatory will service a relatively small area such as the summit of a volcano. The cable, junction box and initial experiments were successfully installed in 1997 and operated for six months until the unarmored cable developed an electrical short circuit to seawater in the rough volcanic terrain.

2) HUGO Design Constraints: In the HUGO case, there are few constraints on the line current or voltage. With no repeaters, the current is only limited by heating. The cable itself can safely carry over 50 A and it was designed for over 8 kV. A 350 V shunt regulator regulates the voltage at the Junction Box. This regulator has two advantages, 350 V allows the use of "low" input-voltage converters at the expense of operating the system at low efficiency and it allows stable operation over the full range of source and load voltages. At initial deployment, the power demands were small, requiring less than 150 W to run the Junction Box. The voltage drop in the cable was thus relatively small and, in principle, no regulation was necessary. In order to deliver the full design power to a fully populated array of experiments, the shore supply could go as high as 850 V at 20 A (17 kW) to deliver 7 kW of power to the observatory. The system is stable over the entire range from 100 W to 7 kW with the shunt regulators, while the power delivery would have been limited to a maximum of 3.5 kW without the shunt regulators.

3) HUGO General Power Information: The heat generated in the shunt regulator and the relatively high likelihood of failure or a desire to replace the shunt regulator, led to the placement of this device in a separate pressure vessel where it could be replaced by a submersible or ROV. A seawater return (negative electrode) was placed away from the Junction Box where it would not effect the cable termination and where it could be easily replaced as needed. The direction of current flow insures that corrosion will occur at the shore-side of the system, rather than on the ocean floor, where replacement of hardware is much more expensive. The return electrode at the shore was buried below sea level in a hole drilled in saturated basalt about 5 m from the shoreline.

4) Diode to Isolate Power: As a precaution, a diode in the HUGO Junction Box prevents current from flowing backward up the cable. This allows the system to be powered by a power-only cable or a battery package, should the conductor in the original cable fail. It also allows us to quickly determine whether a power fault is in the cable or beyond the cable termination. If the diode is still measurable from shore, the cable must be intact. When a connector to the shunt regulator in the HUGO system flooded, this diode was still detectable, indicating that the flooding was not in the main pressure vessel where the diode is located. The diode was critical after the cable to shore developed an electrical fault, allowing a battery package to be plugged into the junction box by a submersible six months after the cable fault. The package powered the system for eight hours until the batteries were drained while data were transmitted to shore over the fibers in the cable.

5) Power to Multiplexer Nodes: Remote multiplexing nodes that could be connected to the HUGO Junction Box would obtain their power from the 350-V dc supply regulator in the Junction Box. Regulation of remote power becomes a serious problem if the resistance of the cable to the multiplexing node is high enough to cause more than about a 25% drop in the source voltage. The Junction Box appears as a constant-voltage

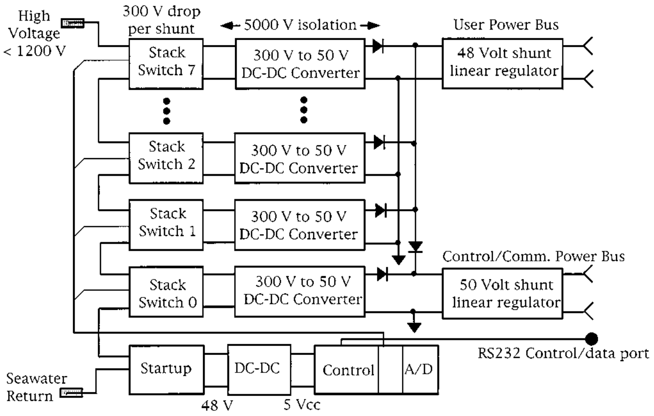

Fig. 3. The Hawaii-2 Observatory uses a stack of relatively low-voltage (300 V) converters to extract sufficient power from the small 370 mA constant current from the cable. At the maximum 1200 V, the input power is 444 W.

350-V source as long as it is active, imposing restrictions on the distance from the junction box to the multiplexer. This problem can be alleviated by stepping the voltage up for transmission to the multiplexer; doubling the voltage cuts the losses by four for a given cable resistance.

C. The H2O Power System

In the second example, we discuss the re-use of long repeatered cables for scientific observatories; in this case an existing trans-oceanic telecommunications cable. The Hawaii-2 Observatory was connected to the Hawaii-2 co-axial SD cable in September, 1998, [3], [4] and is currently in operation. Data are transmitted about 1700 km through the cable to Hawaii, where they are processed and sent to the IRIS Data Management Center in Seattle, WA, for public distribution.

1) Description: An alternate approach to HUGO was required for the Hawaii-2 Observatory power supply, which must draw a constant current of 370 ma from the cable. The Hawaii-2 AT&T SD cable has a resistance of approximately 200 Ω/100 km, causing a resistive drop of 74 V/100 km for the required current [5]. Stacking conventional regulators (with their negative dynamic impedance inputs) would require a floating shunt regulator at the input of *each* converter. The complexity of that configuration would compromise reliability. Instead, we used unregulated (proportional) converters with nominal 300-V inputs and 48-V outputs. When the converter inputs are connected in series and the secondaries are connected in parallel a stable configuration results. A single 48-V shunt regulates the secondary bus voltage. Only the minimum number of converters needed to supply the required power are used. The Stack Switches placed across the input of each converter (shown in Fig. 3) serve to remove unneeded converters from the stack. They also control the voltage rate of change ensuring smooth switching and minimizing disturbances to the constant current in the cable.

2) Advantages: There are numerous significant advantages to this design. These include the following.

1) The proportional converters act as linear "dc transformers". The input characteristics reflect a scaled version of the secondary load, whether it is a lower-voltage regulated converter or a shunt regulator.
2) Stacking height (input voltage) is limited only by the voltage breakdown rating of the transformers in the individual converters. This can fairly easily be 10 kV or more.
3) Load balancing is intrinsic to the design without added design effort or complexity, resulting in enhanced reliability. Since the converter outputs are in parallel (and thus equal voltage), the inputs tend to share the voltage drop equally and since the same current passes through all of the inputs, the outputs share the load current equally.
4) All of the power modules use very conservatively rated standard components. This is very safe (almost boring) technology. A 1200-V switcher would be very risky by comparison.
5) Spare backup power modules can be present in the stack if some means is provided for shorting their inputs when not in use.
6) The expected converter failure mode (a dead short) is actually the preferred condition since it maintains a continuous current path to the rest of the stack. In the event of a module failure, the step-down ratio decreases. In a constant-voltage system, the output voltage drops and the current drawn by the regulated converters increases, but the system should continue to operate without intervention. A backup module can be switched in to restore completely normal operation. In a constant-current system (with a shunt regulator on the secondary), the total available current will decrease until another power module can be brought on line. Some precautions must be taken since a short-circuit failure of one supply in the stack can result in a "domino-effect" over-voltage failure of the other supplies. With conservatively rated converters, this might not become a problem until a significant number of modules failed.
7) Since each module is independent, there is no need to equalize the voltage division of fast switching transients across multiple semiconductor devices. Transient equalization components are a major source of failure and power loss in converters with multiple semiconductors in series. With independent converter modules only slow voltage and current changes need to be equalized.

3) Restrictions Caused by Constant-Current Source: The repeaters in the Hawaii-2 cable require that the termination present a constant-voltage (or slowly varying) load to the cable and that it be capable of operating from a constant 370 ma current source. To deliver more current to the observatory's constant-voltage user load, we must drop more voltage from the constant-current source than commercially available converters (400 V max) can handle. For a 370 ma source, a 300 V drop will consume 110 W and deliver approximately 90 W to the observatory. This requires a constant load at the termination, drawing constant and stable power from the line and dissipating any power not delivered to the observatory. For the Hawaii-2 Observatory, a shunt regulator performs this task, reducing the dynamic impedance at the Junction Box from very high (constant-current) to relatively low (constant-voltage), as required by most practical loads (Fig. 1). Since more experiments will be added to the observatory in the future, potentially up to the full available bandwidth and/or power budget of the system, the system was designed with the capacity for bringing additional power modules on-line to meet increased power demands. In the Hawaii-2 Observatory, eight high-reliability 300- to 48-V converters are stacked to achieve the desired voltage drop (two are dedicated to the junction box system) and to provide redundancy and flexibility over a wide range of power. Such a modular power system can be configured for any input voltage level if the voltage standoff rating of the internal transformers is adequate.

IV. POWER SYSTEMS DESIGN FOR NEW CABLES

Many more options are available when designing the power system for a long, new cable, although the costs of the cable limit these options and thus the power that can be delivered to an observatory.

A. Conductor Considerations

In the best case, a new cable would be designed to the environment and the functional demands of the observatory. If the cable has an adequate conductor, the power delivery constraints can be drastically reduced, and it may be much easier to buy reliability in copper wire than in electronic circuitry. Some cables, such as SL-Light, use an internal strength member (which adds significantly to the copper sheath conductor). On the other hand, for cables with external strength members, additional copper conductor increases the weight and diameter of the cable and in turn increases the weight of the armoring. Careful consideration must be given to these trade-offs in the design of the cable. Reducing copper and depending on strict power regulation to prevent instabilities at high power could very seriously complicate the design and operation and compromise a project. The cable resistance itself will demand a high cable voltage at the shore-end if significant power is to be supplied to an observatory.

B. Long Cable, Single Node at End

Consider an observatory which requires high power delivered on a single cable to a single experiment site (or single local cluster) at a considerable distance from shore. For a cable such as used for HUGO, with a resistance of only 0.75 Ω per km, it is possible to deliver 50 kW at 100 km to a 4-kV load at a 20-A line current and less than 20% line regulation with a 5-kV supply. This is within the range where further regulation may not be required if proper precautions are taken. A converter for a 4-kV load could be implemented with 12 stacked unregulated (proportional) dc–dc converters. With their outputs connected in parallel, they automatically share the output current equally (since their inputs are in series and thus share equal current) and split the input voltage equally (since their outputs are in parallel). While commercially-available regulated converters will not work in this application because of their unstable negative input impedance, the design of a moderate voltage-unregulated converter is straight forward. The 4-kV load could also be implemented as multiple experiments distributed along the cable, although this would require that they all operate at the same current.

C. Repeater Constraints in a New System Design

1) The Problem: Repeaters in submarine cable systems are required periodically along the cable to boost the strength of the communications signal. These repeaters are extremely reliable and changing their design would be prohibitively expensive and risky. Available designs of these devices require a constant-current power system, but running an observatory with branches and loops may not be possible with a constant-current system.

2) A Solution: It should be possible to greatly reduce the serious constraints imposed by the constant-current repeaters by adding a low-voltage shunt regulator across each repeater. The shunt would be designed to carry the excess current around the repeater, such that the cable current could be allowed to vary from the minimum current needed to operate the repeater up to the maximum current safely handled by the shunt regulator. With this approach, it may be possible to use available repeater designs and still have a much greater degree of freedom in power system operation.

3) Example: For a relatively simple example using shunted repeaters, consider a 2,000-km long cable (75 Ω/100 km) with no branches and with a science node and repeater every 100 km along the cable. By supplying 6 kV at the shore at about 2 A, a 3 kV drop from the cable resistance would be observed, leaving 3 kV for use by the twenty science nodes and repeaters. The Shore Station would supply a maximum of 18 kW of power and the drop across each repeater/science node would average 150 V, for a delivered power of 300 W per node. All nodes would be forced to run at the same current, but the voltage drop and thus the power supplied to each node could be adjusted according to the demands at that node. It should be noted, however, that the dc–dc converters have an efficiency of about 80%–90% and some additional power would be required by the shunt regulators to stabilize the impedance of the network.

4) Alternative Solution: It is important to consider an alternative. The same cable configuration can operate at 25% maximum voltage drop. With a 6-kV, 1-A source, the cable-voltage drop is 1.5 kV, leaving 4.5 kV for the load and a total load power of 4.5 kW. With the same 20 repeaters as above, the voltage drop per repeater/node is 225 V and the power per node is 225 W. The dc–dc converters can easily handle the 25% line regulation. In this case, the power delivered is somewhat lower (225 W versus 300 W) but the power system will be stable even without shunt regulators. The added system complexity and the power drain of the shunt regulators in the above example diminishes the power advantage of the first example considerably. A 20% reserve current in the regulators would reduce the power advantage to only 10 W per node. Low-voltage shunt regulators would be required at the repeaters in both examples to permit a higher (and variable) line current.

V. FUTURE OBSERVATORIES

Future ocean floor observatories are likely to have several branches, loops in the main cable and heavy power demands. The power supplied to such systems will be limited by the cable characteristics, the array configuration and load demands. Power management will be challenging, as shown by the relatively simple model below.

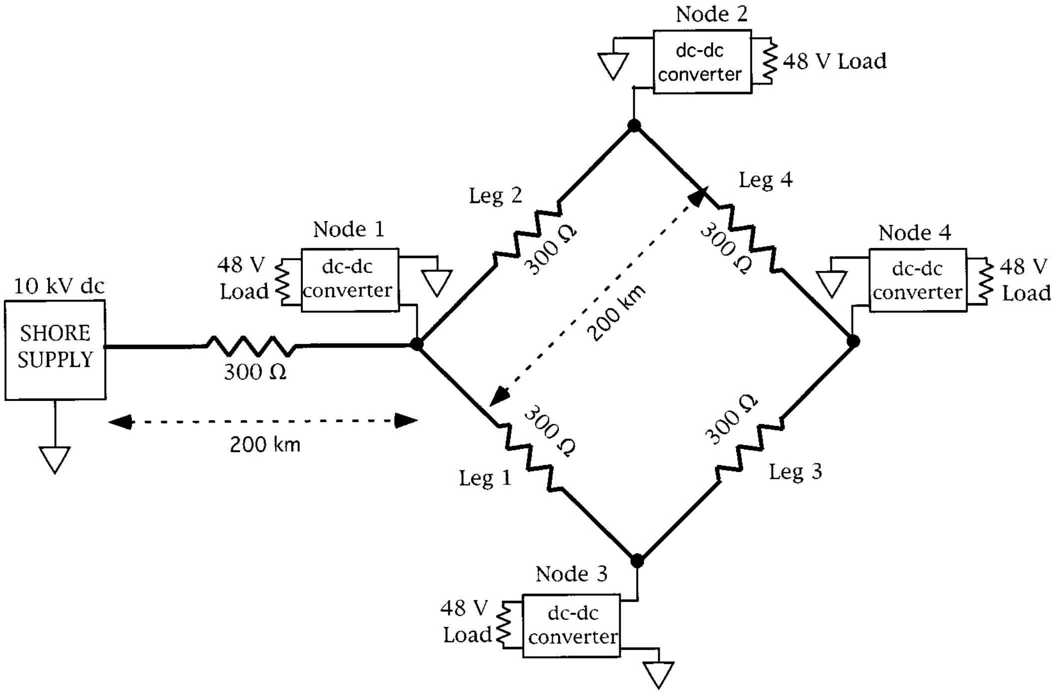

Fig. 4. Schematic of PSPICE model for a complex cabled observatory.

A. Simple Model

To illustrate the design problems of an ocean-bottom science array, consider a fairly simple array consisting of four nodes in a diamond configuration. While this model represents the simplest form of envisioned observatories [6], the concept of a loop with multiple nodes is adequately modeled. The diamond-shaped array provides a degree of redundancy. If there is a fault in any one side, limited power can still be provided from the other direction. Considering the costs of repair, this redundancy could greatly enhance the utility of the system. While we use a 10-kV or higher source voltage in this model, we recognize that risks are involved in the use of such a high voltage in the ocean, particularly in systems with underwater make-and-break connectors. Commercially available connectors conservatively rated for 10 kV are not yet available.

1) Unregulated System: The first node in the model is 200 km from shore and the arms of the diamond are each 200 km long. The cable has a dc resistance of 1.5 Ω/km (Fig. 4). For the purpose of this example, an idealized model of the regulated dc–dc converter was used at each node (without shunt regulation). The input to each node follows a constant-power curve from 2000 to 10 000 V. Below 2000 V, the converter is unable to maintain regulation and the output sags proportionately. Note that while the model converter can operate down to 20% of the input voltage, the network collapses at about 50% of the 10-kV source voltage, implying that the low-voltage performance of the converters does not affect the stability of the system. The model does not account for converter losses; the power provided by real converters would be 80%–95% of the input power.

For this analysis, the four nodes draw equal power as the current is increased until the power to each node reaches about 15 kW (about 60 kW total), at which time the power collapses suddenly. As the voltage drops, the current drawn by the node rises sharply. When this unstable condition occurs, all of the other nodes also immediately begin to pull more current from the system, accelerating the collapse. In some models, the collapse occurred in less than 10 ms, implying that no time would be available to prevent collapse once it had started, and the conditions approaching collapse must be avoided by a wide margin [Fig. 5(a)]. Notice that the power collapses when the input voltage to the most-remote node reaches approximately 50% of the source voltage.

e) Fault conditions: To simulate a fault situation, Leg 2 (Fig. 4) was cut and the process repeated. The longest cable path (going around the array) is 800 km. The array now collapses at about 9.5 kW per node (38 kW total). When one of the farther legs (Leg 4) was cut, the remote node no longer has parallel current paths and so the total power is reduced. But since the longest path is only 600 km, the power is not curtailed as much as when the nearer leg is cut. The array collapses at about 13.8 kW (about 55 kW total).

2) Regulated System: In the test shown in Fig. 6 shunt regulators are added to the nodes in the original array. The shore voltage was then boosted from 10 to 13.6 kV. The shunt regulators are set to 8.2 kV (Node 1), 6 kV (Nodes 2 and 3) and 5.2 kV (Node 4). Note that the power available per node approximately doubles from 13.5 to 27 kW. The node voltages remain virtually unchanged over the full power range due to the action of the regulators, but when a regulator current drops to zero (and thus ceases to provide regulation) collapse occurs without warning. This is true for even a millisecond loss of regulation.

B. Branches and Loops

Future observatories may require several branches and loops in the cable and many science nodes spaced along the cable. This

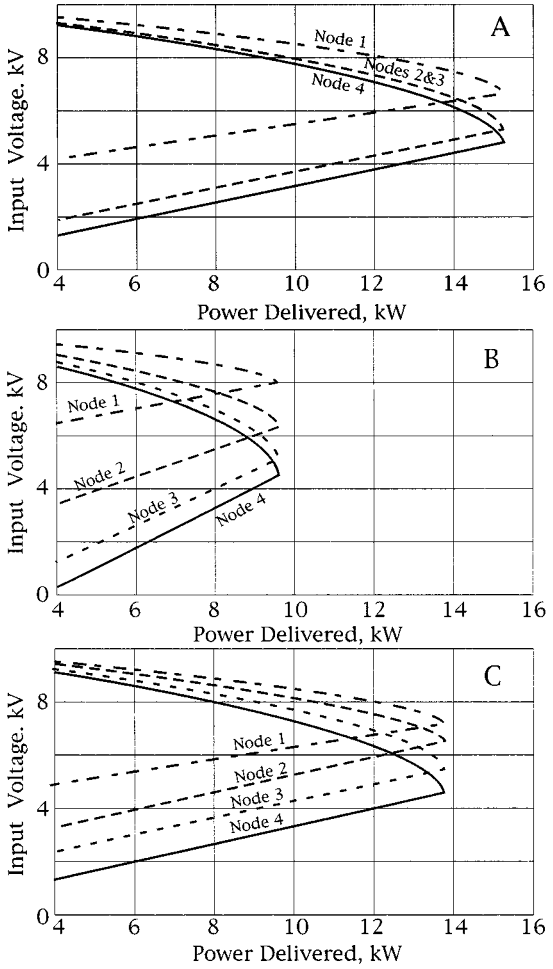

Fig. 5. Model power grid collapse. (a) intact array. (b) Leg 2 cut. (c) Leg 4 cut. The vertical axis is the voltage at the input to each node. In all cases, equal power is delivered to each node, the source voltage is 10 kV and current is increased until collapse occurs.

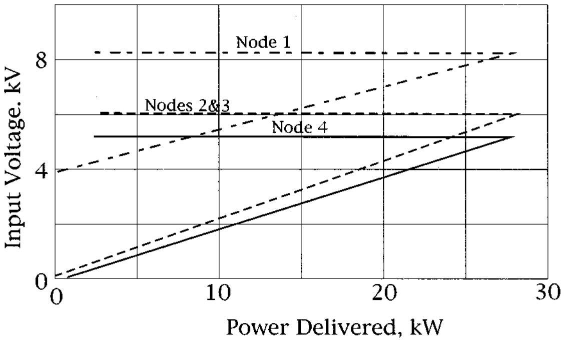

Fig. 6. Array with shunt regulators. The voltage at the input to each node is regulated by a shunt regulator. Power supplied to the nodes is about twice that possible without regulation since the shore voltage can be increased beyond the region where the unregulated system is stable. Collapse is abrupt and without warning.

complicates the picture far beyond the example above. Since changes in any one load cannot be allowed to adversely affect the power supplied to any other node, the complexities of power distribution become quite interesting. Modeling a system mathematically with multiple real-positive and negative impedances plus reactive components (cable capacitance) is very difficult. There are virtually an infinite number of combinations of loads that might eventually occur as new experiments are deployed. The general "rule of thumb" is to use a high enough voltage (and thus low enough current) so that no part of the system is in the range where more than about 25% of the last regulated source voltage is being dropped in the cables. High-voltage, low-current, and low-cable resistance will result in the most favorable power delivery.

1) Dead-End Branch: In the case where the main cable branches to a dead-end, the probability exists that the relative impedances of the branches will be far from ideal due to differences in cable resistance (length) and power demands. For example, a short branch near shore might have a very high operating voltage just to run a small load. That voltage may vary over a considerable range while optimizing power delivery to the rest of the array. One approach to this problem would be to generate a regulated and isolated voltage to power the branch, but that would require either a two-conductor branch cable (doubling the cable losses) or a positive (sacrificial) seawater return electrode at one end or the other. Each science node (and repeater) along the branch would then have to obey the "25% rule" to maintain stability. In a relatively static array, it may be possible to configure a symmetrical "Y" branch, which will passively split the cable current between the two branches.

2) Power in Loops: In the case where power is (or could be) supplied from both directions around a loop, consideration must be given to the case where one branch is damaged. This requires either that each branch have a low enough resistance to supply the full load, or that the maximum load be limited in the event of a failure of one branch of the cable. Any break in a cable will almost invariably result in a decrease in the maximum available system power. If the system is lightly loaded, the operation may continue uninterrupted. If circuit breakers do not automatically reduce the load, it may be necessary to shut down and re-power the system. In either case, it will probably be necessary to make adjustments to optimize the power distribution. If power is to be supplied from either direction along a cable loop, then regulated systems will likely need to be reprogrammed to accommodate the lower power. Note that in the example shown in Fig. 6, the power going to Nodes 1, 2, 3, and 4 is shunt regulated to 8200, 6000, and 5200 V, respectively. When Leg 2 is cut, the voltage at Node 2 will always be less than 5200 V, thus, the shunt regulator at Node 2 will not be functioning and the system will collapse. In order to accommodate the condition of the damaged cable leg, all of the shunt regulators would have to be re-programmed to optimize the power delivery in the new configuration.

VI. SUMMARY

A. Stability

The ideal system would have a low enough cable resistance to deliver sufficient power to each node with less that 25% drop from the cable source voltage. Such a system would probably be stable even without shunt regulators. A stable ocean-bottom power system with nearly any load configuration can be operated without regulation if enough power can be supplied from shore. However, the practical limitations on copper in the cable will limit power and the necessity of changing loads in experiments will require considerable control of each separate load from shore. A key factor for delivering the maximum amount of electrical power will be to reduce the resistance of the cables as far as economically possible. Far more money and effort could be spent in compensating for a resistive cable than for extra copper.

B. Regulation

In constant-current systems and in systems with excessive cable resistance for the required power, regulation is required to stabilize the system against the effects of regulated dc–dc converters. The increased stability comes at the expense of reduced efficiency. With a shunt regulator, experiment loads can be changed without affecting the cable power or other nodes. The excess power at each junction can be measured locally and power above a reasonable overhead is available for use by experiments at that node. If, however, the regulator current drops to zero for even an instant in a system operating in the unstable region, the power system will collapse. This is important since some user loads may draw 2–5 times their normal current during startup. Beyond about 30% voltage drop, the shift in operating point with changes in user demand is magnified, reaching 2:1 at 40% drop and 5:1 at 45% drop. To allow for load fluctuations, the cable voltage drop should generally be limited to less than 25% for stable loads and even less for fluctuating loads. A mix of regulated and unregulated circuits might be optimal for maximum power delivery.

C. Capacitance

Repeater power stability requirements and cable capacitance may place constraints on the maximum rate of change of voltage at the load.

D. Modeling

The design of a power system for a long cabled observatory on the ocean floor with distributed loads and branches will require a very significant modeling effort to ensure the design of a viable power system, but no amount of modeling will be able to anticipate the myriad of situations possible in a complex system.

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