FAU Institutional Repository

http://purl.fcla.edu/fau/fauir

This paper was submitted by the faculty of FAU's Harbor Branch Oceanographic Institute.

Notice: ©1991 Marine Technology Society. This article may be cited as: Tusting, R. F., & Taylor, L. D. (1991). Modern power distribution and conversion in undersea systems. *MTS '91: an ocean cooperative: industry, government & academia: proceedings. Vol. 2.* (pp. 911-917). Washington, DC: The Society.

MODERN POWER DISTRIBUTION AND CONVERSION IN UNDERSEA SYSTEMS

Robert F. Tusting and Larry D. Taylor

**Harbor Branch Oceanographic Institution, Inc.
Fort Pierce, Florida**

ABSTRACT

Power distribution and control has always been a challenge to designers of undersea systems. The high current demands of main power loads such as propulsion, hydraulics, lighting and machinery must be met while providing well regulated, noise-free power to instrumentation and sensor systems. Fortunately, recent advances in power conversion technology have made this task easier.

This paper will briefly review the electrical power requirements of undersea systems, describe the characteristics of the newest high efficiency, compact power converters and present several practical power system examples.

INTRODUCTION

Electrical Power for undersea systems is either high-voltage single or poly-phase alternating current (ac) or high or low voltage direct current (dc). The power is generated within the system, or it is delivered thru conductors (transmission lines) from sources on the surface. Problems encountered with these systems are poor regulation, large fluctuations, and high noise.

Typical cabled systems are remotely piloted vehicles (RPVs) and "over-the-side" instrumentation such as profiling equipment, hydrophone arrays, etc. The small cabled instrumentation systems are often operated with low voltage dc power rather than ac to provide easier separation of the signal spectrum from that of the power system.

Self contained systems are either free-swimming vehicles such as manned submersibles and autonomous undersea vehicles (AUVs) or in situ deployed instrumentation packages. Most commonly power sources for these systems are battery packs that must be recharged (or replaced) with time and use. Some systems (such as manned submersibles and torpedoes) use thermal power sources or internal combustion engines for major improvements in endurance (1,2).

POWER SYSTEMS FOR RPVs

Remotely piloted vehicles usually operate on ac power provided from a support vessel through a cable which also provides the communication link. Notable exceptions are the French PAP-104 mine-hunting vehicles which have on-board batteries and are linked to the surface by a small fiber-optic cable.

High voltage power is generally transmitted to reduce the size and weight of the cable. It is not uncommon for the weight of the umbilical cable to be many times the in-air weight of the vehicle.

The high-voltage ac power is converted to more manageable voltages (480V or less) at the lower end of the cable. Conventional 50 or 60 Hz power components are most commonly used for design and fabrication economy. However, higher operating frequencies can produce significant size and weight-reduction advantages.

In some cases, notably low-cost vehicles and extremely deep systems (where the small tether diameter associated with a coaxial, high-voltage transmission line is important) single-phase power is used (3).

POWER SYSTEMS FOR FREE-SWIMMING VEHICLES

The main battery systems for small manned submersibles and AUVs such as those used for exploration, research, and intervention tasks, can be divided into two categories: low voltage (24/28 Vdc) and medium voltage (100 to 120 Vdc).

There are a few vehicles that operate at 210 Vdc and 12 Vdc (primarily recreational) but most power systems use 24/28 V or 100 to 120 V batteries.

24/28 Vdc Power Systems

These low voltage systems are common because a large selection of high-quality electrical components have been designed to operate at 24 to 32 Vdc. This is the primary power voltage of military aircraft and many marine systems. Inexpensive, high-reliability motors, relays, circuit breakers, etc. have been available from surplus sources for many years.

The main reason for choosing this voltage is based on fundamental physics; it is difficult to interrupt a high-current arc in many gases (i.e., air) if the voltage is greater than approximately 50 Vdc. Switches, relays, fuses, and circuit breakers which operate reliably at 28 Vdc are not fail-safe at higher voltages. This is the reason many of the vehicles designed in the 1960s and 1970s (for example JOHNSON-SEA-LINK I and II) used a 28 Vdc battery as the primary power source.

Many important operational and emergency systems for example, underwater telephones, pingers, instrumentation, etc. are designed for 24/28 Vdc operation. The electrical shock hazard is also considerably lower at 28V than it is at 120V.

120 Vdc Power Systems

The U.S. Navy/Woods Hole ALVIN, was converted in 1986 from a 60 Vdc power system to a 120 Vdc system (4). The ALVIN emergency battery system remains 28 Vdc, however, as are the backup or emergency battery systems of most manned submersibles.

The primary advantage of increased voltage is that wire size (and weight) is reduced significantly as the voltage of the power system is increased. A 120 volt circuit requires electrical conductors which weigh approximately 6 percent as much as those in a corresponding 28 volt system. A reduction in electrical conductor weight on a vehicle can result in an increased payload or a decreased total vehicle weight. Many commercial devices operate on 120 Vdc, for example there is a much greater selection of high wattage (>200 W) lights designed for 120 Vdc than there is for 28 Vdc. Motors, solenoids, and other electro mechanical devices are readily available for 120 volt operation.

However, power control components are problematic, and the design of a 120 Vdc power distribution and control system is more difficult than that of a low-voltage system (4,5). For example, 120 Vdc relays can be designed with internal permanent magnets which cause a strong magnetic field in the vicinity of the electrical contacts. When the relay is opened, the charge carriers in the plasma arc aredeflected sufficiently so that the arc is not maintained and the current is interrupted. Another technique is to connect several pairs of contacts in series so that when the relay is opened the arc voltage across any one set of contacts becomes low enough to extinguish the arc and allow the circuit to open. Special high-voltage fuses have also been developed which are spring loaded and mechanically eject themselves from the circuit in event of overload. Solid-state relays and contactors are another approach, but as with other power control devices, it is essential to verify that they will be reliable under fault-conditions and abnormal operations.

Alternative Systems for AUVs

The electrical power systems for AUVs are typically 120V secondary batteries, but improved power sources such as high-energy-density batteries, fuel cells, and high-efficiency engines are under development for increased endurance missions (1,6,7). A number of proposed systems are designed around Stirling engines for propulsion with electrical loads being supplied by batteries recharged by the engine (1).

THE MODERN DC-TO-DC CONVERTER

One of the most useful innovations in power conversion during the past 10 to 15 years is the development of the modern, high-efficiency, high-energy-density dc-to-dc converter (refer to Figure 1). These devices solve many power system problems by providing:

- Well-regulated voltage from poorly regulated power buses
- Voltage conversion (both up and down) to suitable levels for operating electronic circuits and efficient transmission
- Good electrical isolation from the main power bus and between several interconnected electronic subsystems

Converters are available in sizes from a fraction of a Watt to several kilowatts with conversion efficiencies of up to 90 percent for some of the more-efficient types such as the one shown in Figure 1.

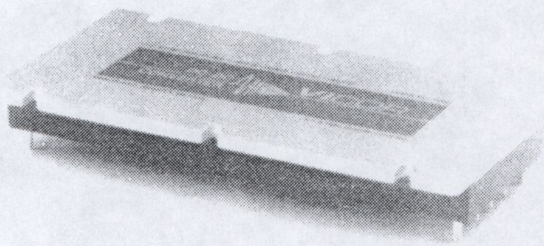


Figure 1. A modern dc-to-dc converter. The output power is 200 watts from a package 4.7 inches by 2.4 inches by 0.5 inches.

High-frequency operation, combined with modern switching components and innovative design, provides compact units with power densities of up to 50 Watts of output power per cubic inch (8). Some dc-to-dc converters operate on a wide input voltage range (for example, 9 to 36 so that they can be used with a variety of power systems (i.e., 12 or 24/28 Vdc).

The Dc-to-Dc Converter as a Line Transformer

Because of their high-efficiency, moderate-cost, and compact size, these power converters are nearly ideal building blocks for undersea power systems and instrumentation. They are particularly useful as dc step-up and step-down transformers for applications where power must be transmitted through long cables.

As an example, consider the simple case where a 12 Vdc, 12 W load (1 Amp) is to be operated at the end of a long cable having a total series resistance of 30 Ohms. A 42 Vdc source would be required and 71 percent of the supplied voltage would be dropped in the series resistance of the cable. In addition, the voltage regulation at the load would be very poor.

Instead, consider the use of a 100 volt-input dc-to-dc converter at the terminal end of the cable and transmitting a higher voltage at lower current as illustrated in Figure 2. Assuming a 75 percent conversion efficiency of the converter, 16 watts would need to be supplied at 0.16 Amps. The voltage drop in the cable would be less than 5 percent and the load would be supplied with well-regulated power.

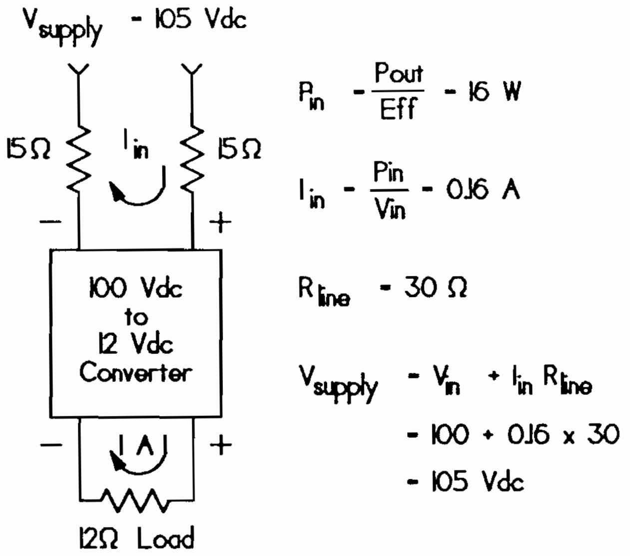


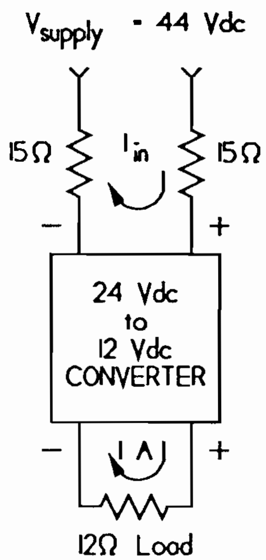
Figure 2. Application of a dc-to-dc converter as a voltage step-down transformer.

Negative-Resistance Characteristics of Dc-to-Dc Converters

One of the inherent characteristics of a dc-to-dc converter its negative input resistance. This intrinsic behavior can be problematic for cases where the converter is powered from current-limited sources or from high-impedance power distribution systems, for example, through a long cable. As with negative-resistance devices in general, it is possible to excite oscillations. With modern converters and proper design, this situation can be avoided.

To illustrate the problem of a high impedance between the power source and the input terminals of the dc-to-dc converter, consider the above example in which a 12 Vdc, 12 W load is to be powered from a 24 Vdc to 12 Vdc converter at the terminal end of the cable rather than the 100V converter of in Figure 2.

This situation is shown in Figure 3. For this example, 20 volts of the applied voltage would be dropped in the cable resistance. But the situation is much worse; The converter will fail to deliver 12 volts to the load! To explain, consider the graph of Figure 4 in which the input current required by the converter is plotted as a function of input voltage. For simplicity, the converter efficiency is assumed to remain constant at 75 percent over the normal input operating range, in this case 18 to 30 Vdc. Also plotted in Figure 4 is the relationship between the current and voltage that can be supplied by the external 44V power source in series with the 30 Ohm cable resistance (this curve is called the circuit load line).



$$P_{in} = \frac{P_{out}}{Eff} = 16\ W$$

$$I_{in} = \frac{P_{in}}{V_{in}} = \frac{16\ W}{24\ V} = 0.67\ A$$

$$V_{supply} = V_{in} + I_{in} R_{line} = 24 + 20 = 44\ Vdc$$

Figure 3. Circuit to illustrate the negative-resistance behavior of a dc-to-dc converter.

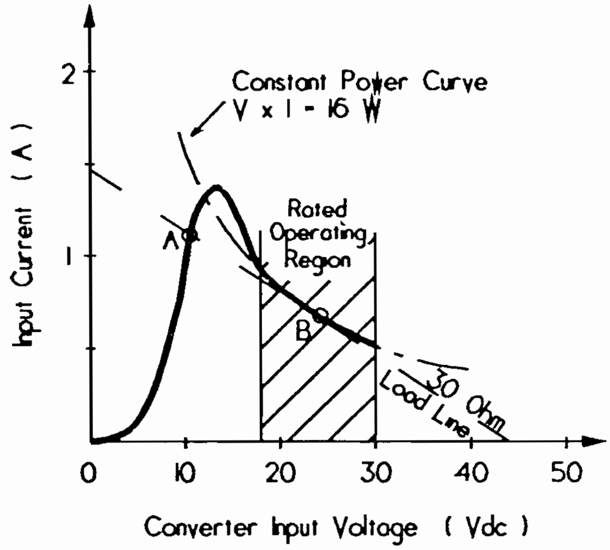


Figure 4. Input current vs. input voltage characteristics of an idealized 24V-to-12V converter with a 12 Watt load and a 75% efficiently.

When the supply voltage is initially applied, the converter will "hang-up" at the low-voltage, high-current point A of Figure 4 drawing approximately 1.1 Amps at an insufficient voltage of 11 volts. Under this condition, the converter cannot operate properly and will likely be overheated and damaged. A small increase in supply voltage will have the effect of moving the load line upward to create a bi-stable situation which could result in the circuit oscillating. A further increase in supply voltage would over-voltage the converter and probably destroy it. Using a current-limited power supply with insufficient current capacity will result in essentially the same situation illustrated in Figure 4.

The solution is to use a higher supply voltage so that the cable resistance does not dominate the power-transmission-system characteristics. The other (more costly) approach would be to obtain a lower resistance cable.

Many of the first generation dc-to-dc converters exhibited an even more pronounced peak in the input-current versus input voltage curve than that shown in Figure 4 requiring up to four times the rated input current to "get over the hump" and into the normal operating region. Modern converters, such as the one shown in Figure 1, have additional circuits which provide logic level control and inhibit operation unless the input voltage is adequate.

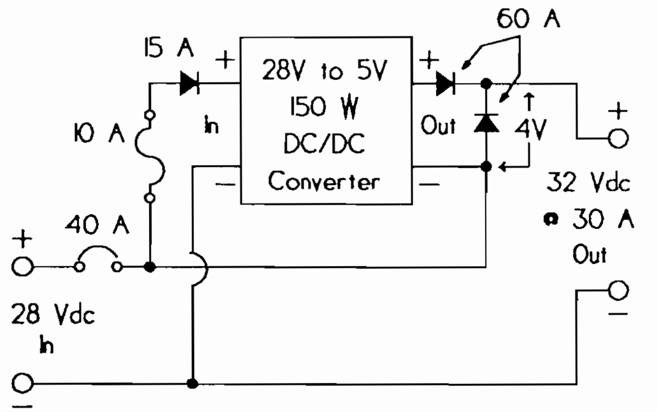


Figure 5. Power booster for converting 28Vdc to 32Vdc with high efficiency.

The Dc-to-Dc Converter in Power Distribution Systems

In battery-powered underwater systems, dc-to-dc converters provide a convenient way to obtain power at voltages other than that of the primary battery. For example, a 120 Vdc to 28 Vdc converter (or bank of converters) can provide a regulated and isolated low-voltage power bus from the main battery pack. This is a much more efficient approach than the common practice of using a low-voltage tap from the battery.

Another application is to provide a voltage boost for a load that requires somewhat higher voltage than the main battery can provide. This approach is illustrated in Figure 5 in which 32 Vdc at nearly 1 kW is obtained from a 28V battery. With a converter efficiency of 80 percent, the overall efficiency of the circuit is approximately 94 percent. The output voltage in this case is not regulated, but is always 4 Vdc greater than the input voltage.

THE MODERN INVERTER

Battery powered undersea systems also include equipment which is designed to operate on ac power. Examples are:

- Search sonars
- Gyro-compass repeaters
- Pan and tilt units
- Laboratory-based equipment
- Ballasts for high efficiency lights

Power from the main dc source is converted to ac power by a device called an inverter. Early versions of inverters consisted of dc motors mechanically driving ac generators and oscillating relay that produced essentially square output waveforms. Modern inverters use much of the same electronics as dc-to-dc converters and include programmable switches to synthesize a low-harmonic-content ac voltage. A good example of this technology is shown in Figure 6. This inverter, manufactured by Avionic Instruments, Inc. provides 250 watts of well regulated 60 or 400 Hz power from 28 Vdc nominal input voltage. This design weighs less than 5 lbs. which is a factor of 10 improvement over a rotatingmachinery type inverter. A wide range of other units including poly-phase inverters are available using the same technology.

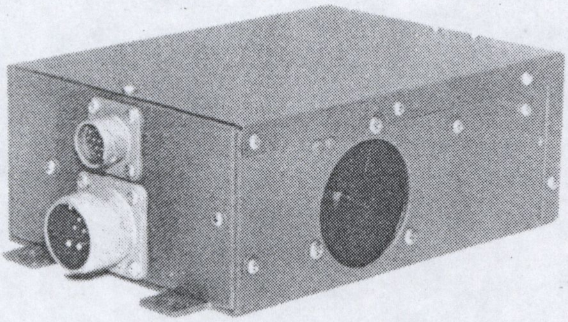


Figure 6. A high-efficiency, solid-state inverter which provides 250W of low-distortion ac power. The size is 5.25 inches by 2.75 inches by 8.5 inches including mounting brackets.

Inverters which operate with an input voltage of 100 to 130 Vdc are also available but the existing designs are based on uninterruptable power source technology. These inverters are bulky and heavy and are used where weight and size are not a major consideration. Lightweight, high-energy-density 28 volt static inverter technology could readily be adapted to 100 to 130 Vdc power systems. All that is needed is a sufficient demand to justify the development cost.

ACKNOWLEDGEMENTS

The authors would like to thank Annell Nelson for editing and typing the manuscript. This work was primarily supported by internal funds and is Harbor Branch Oceanographic Institution Contribution No. 858.

REFERENCES

1. Hawley, J.G., I.J. Potter, and G.T. Reader, Thermal Power Sources For Extended UUV Mission Requirements, Proceedings Under Sea World '91, pp. 110-117, West Star Productions, 1991.

2. Robinson, Richard C., National Defense Applications of Autonomous Underwater Vehicles, IEE Journal of Oceanic Engineering, Volume OE-11, No. 4 pp. 462-467, 1986.

3. Wilkins, George, Tradeoffs in Optimization of Deepsea Electro-Optical Cables, Proceedings Fifth OMAE Conference, Tokyo, Japan, 13-17 April. 1986, ASME, 1986.

4. Hosom, D.S., N.C. Forrester, and B.B. Walden, ALVIN - 120 VDC/28 VDC Electrical System, Proceedings Oceans '87, pp. 1272-1277, IEEE, 1987.

5. Endo, Michimasa, 2000 m Deep Submergence Research Vehicles "SHINKAI-2000,"Proceedings Oceans '82, pp. 41-49, IEEE, 1982.

6. Herr, William J., AUV Technology Development and Demonstration Program. Proceedings Oceans '88, pp. 1290-1299, IEEE, 1988.

7. Moore, John Jr., Editor, Power Systems for Small Underwater Vehicles, MIT Workshop Proceedings, MITSG 88-11, 1988.

8. Cogger, S.D., Dc-to-Dc Converter Family Packs Power Into Tight Spots, Electronics Design Magazine, February 19, 1987.