Current-to-Current Converter for Scientific Underwater Cable Networks

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***Abstract*—A new current-to-current converter, which is a key device to branch a constant direct current (dc) into two constant dcs, was proposed [K. Asakawa *et al.*, Proc. OCEANS, pp. 1868–1873, 2003]. It has been verified, through computer simulations and experiments using prototypes, to have good conversion efficiency and stable operation. Because the basic circuit is simple, high reliability is expected. The current-to-current converter is a key device to realize a constant current (CC) power-feeding system for scientific underwater cable networks having mesh topology, which is necessary to enhance robustness against cable breakdowns and to deploy sensors in 2-D and efficiently over a vast research area.**

***Index Terms*—Constant current (CC), current-to-current converter, scientific underwater cable network.**

I. Introduction

SCIENTIFIC underwater cable networks are anticipated to be the most promising means to achieve continuous real-time, long-term, and 3-D underwater observation covering a wide region, which is necessary to elucidate the nature of oceans and the earth.

Accelerated by the recent evolution of the submarine optical cable technology and related technologies such as computers, Internet, electronics, etc., several ambitious scientific underwater cable network projects have been proposed and initiated. The United States and Canada have commenced the joint project called the Northeast Pacific Time-Series Undersea Networked Experiment (NEPTUNE),[1] which will emplace a scientific underwater cable network in the northeastern Pacific Ocean. In Monterey Bay, CA, and in the ocean around Victoria and Vancouver, Canada, respectively, the Monterey Accelerated Research System (MARS)[2] and Victoria Experimental Network Under the Sea (VENUS)[3] projects are also underway. In Europe, the European Seafloor Observatory Network (ESONET)[4] consortium has proposed ten scientific cable networks in the submarine terrain around Europe. These networks will be used for multidisciplinary investigations including those of geophysics, oceanography, biology, chemistry, biochemistry, and fisheries.

In Japan, eight scientific underwater cables have been constructed and they currently operate [1]. Because Japan is located near plate boundaries where catastrophic earthquakes and tsunamis occur periodically, seismology has a higher priority in view of disaster mitigation.

Considering the previously described situations, the IEEE Oceanic Engineering Society Japan Chapter has organized a technical committee to promote a technical feasibility study [2], [3] of scientific underwater cable networks. The committee was established in February 2002 [9].

The proposed scientific underwater cable network [2], [3] is named advanced real-time earth monitoring network in the area (ARENA). Although the main mission of ARENA is seismic observation, it is intended to be used multidisciplinarily.

Fig. 1 shows that ARENA has a mesh topology, which facilitates deployment of sensors over a vast observation area. It has multiple landing stations. Various sensors are connected to cables through underwater hub units. The mesh topology is also effective to increase robustness against cable shunt faults. Because the cable network is connected to multiple landing stations, each observation node has plural routes to landing stations. For that reason, even if one route is broken, it will be linkable to another landing station through another route and observations can continue. This feature is necessary, especially as a countermeasure against cable faults caused by earthquakes because it is a rare chance to observe aftershocks and it is very important for disaster mitigation and seismic studies.

In ARENA, underwater telecommunication cables will be used as trunk cables because they have superior reliability. Their configuration is simple and their cost is moderate. All related technologies and tools for construction and repair work are available. Because only one electric conductor exists, as shown in Fig. 2, in the underwater optical telecommunication cable, the return current flows in the seawater.

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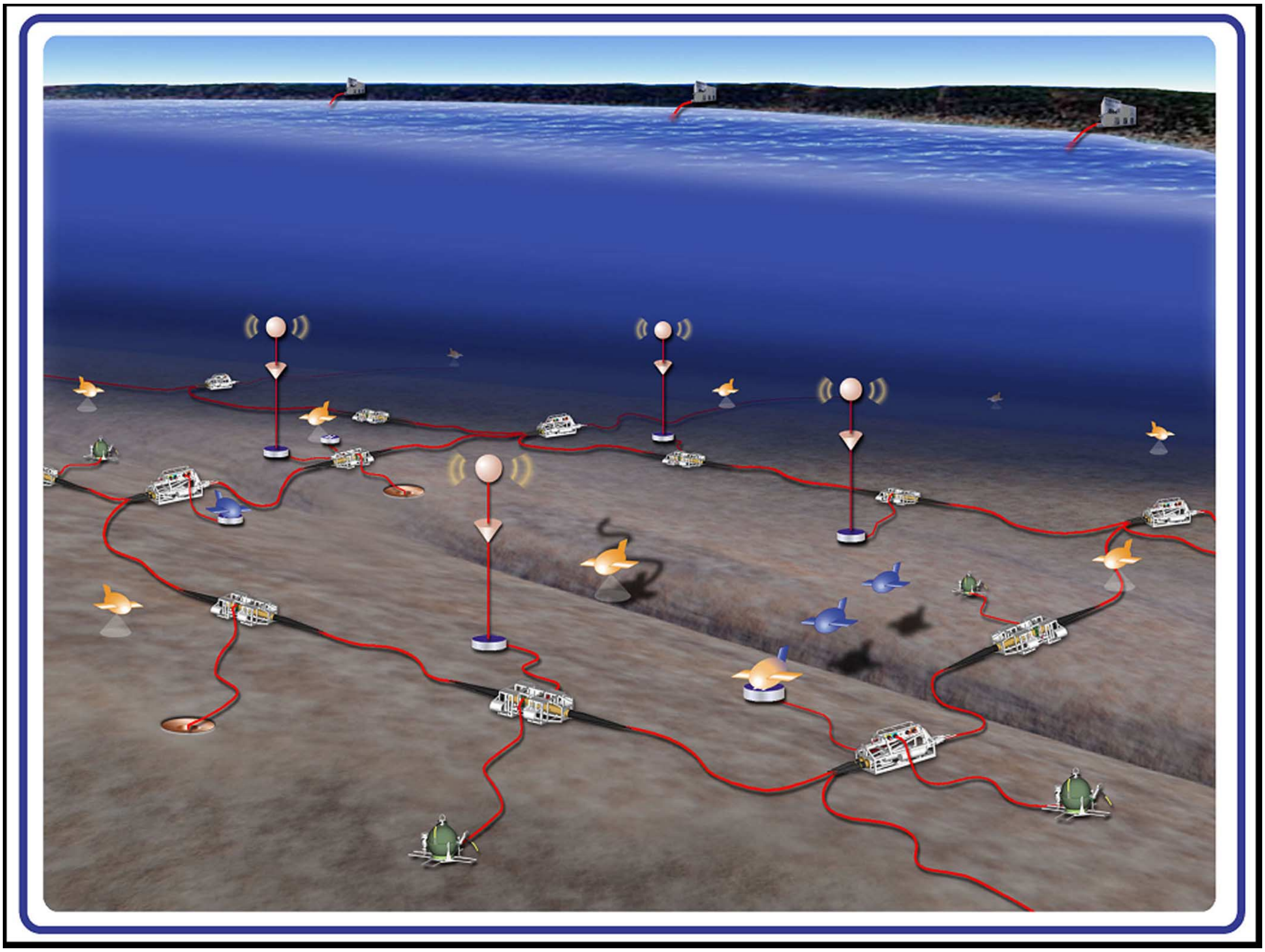

Fig. 1. Image of ARENA.

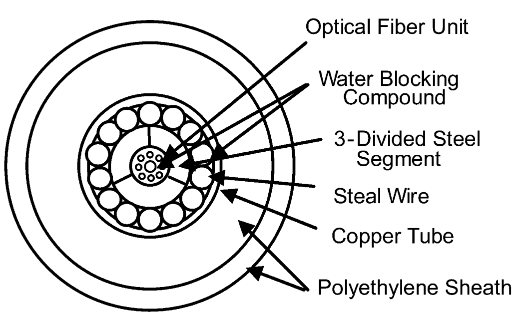

Fig. 2. Typical cross-sectional view of lightweight optical telecommunication cables.

For conventional underwater telecommunication cable systems, a constant current (CC) power-feeding system is used, because it has the following advantages.

1) It is robust against cable shunt faults. Because electric power is usually supplied from both ends of the cable, even if the cable is shunted to seawater at one point, electric power can be supplied continuously to the entire cable from both ends. Only the electrical potential distribution of the cable changes.
2) In case of a cable shunt fault, the fault point can be localized by measuring the direct current (dc) resistance between the power-feeding line and the sea earth.
3) It is easy to isolate underwater electric circuits in repeaters electrically against seawater because there is no sea earth brought into repeaters.

In case of shunt faults where current is flowing in from seawater to the conductor, electric corrosion will not occur and we can continue to supply power. However, in case of shunt faults where current is flowing out from a fault point to seawater, the exposed conductor will corrode and the shunt impedance will increase. In such a case, one means to continue to supply power is to reverse the polarity of the current. Repeaters and current-to-current converters should be bipolar. Adding a rectifying circuit at the input stage, repeaters and current-to-current converters are easily rendered bipolar.

In the feasibility study, the three following power-feeding systems were compared:

1) CC power-feeding system;
2) constant voltage (CV) power-feeding system;
3) hybrid system that includes a CC power-feeding system and a CV power-feeding system.

Advantages for a CC power-feeding system for telecommunication cable systems mentioned previously are applicable

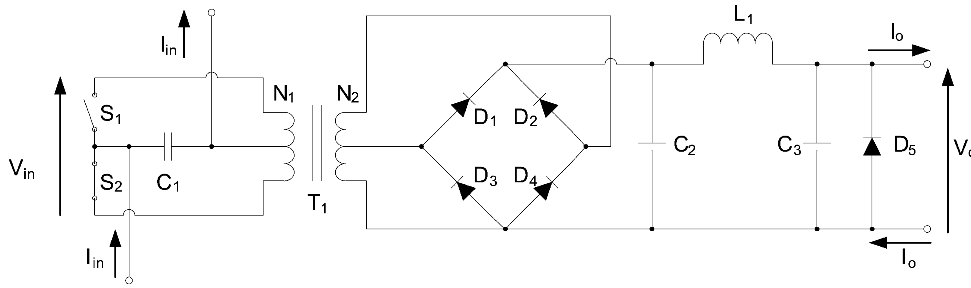

Fig. 3. Basic circuit diagram of the current-to-current converter.

to scientific cables, except for item 3), because a node or a branching unit will necessitate a sea earth in the housing. However, there was no device to divide a CC into two CCs. Such a device was necessary to supply a CC to cable networks having mesh topology. On the other hand, a CV power-feeding system presents the advantage of easily dividing a CV power supply line into plural lines [4]. It is also suitable to provide large electric power because it is easy to divide electric power. The NEPTUNE system adopted a CV power-feeding system [5], [6], which is now being developed. However, a new method should be developed to find cable shunt faults and to remove faulted sections to continue operation when shunt faults occur. Power supply systems in underwater devices must be more sophisticated than those for CC power-feeding systems, because electric power for underwater devices should be taken from higher dc voltage of several kilovolts.

The authors have proposed a new current-to-current converter [7], which is a key device to divide a CC into two CCs. It enables construction of a mesh-like cable network with a CC power-feeding system. Results of experiments using two prototypes and results of computer simulations are presented in this paper. These results show promising characteristics of the proposed current-to-current converter.

II. Basic Circuit

Fig. 3 shows a basic circuit diagram of the converter. The input dc current $I_{\rm in}$ is switched with switching devices such as metal–oxide–semiconductor field-effect transistors (MOSFETs) and is converted to the alternating current (ac) and input to a transformer. The output current of the transformer is rectified to produce another output dc I_o. The ratio between the input and the output current I_i/I_o is almost equal to N_1/N_2 where N_1 and N_2 are the winding numbers of the transformers. The magnitude of the output current is almost proportional to the magnitude of the input current. In other words, if the input current is constant, the output current will also be constant; the current-to-current converter divides a CC into two CCs. In the design of the prototypes, we made N_1 and N_2 equal.

Because the basic circuit is very simple and no feedback loop exists, high reliability and high conversion efficiency are expected.

Overvoltage and overcurrent sensors are put in the input stage, but they are not shown in Fig. 3. The overvoltage sensor is used to protect the converter in case of high impedance fault in the cable. To increase the output voltage and the power, inputs and outputs of plural converters are connected in series, as depicted in Fig. 4. Because current-to-current converters will be placed on the seafloor, and because it is not easy to recover and repair them when they fail, higher reliability and robustness are required. In Fig. 4, converter-4 is shown as a standby; its input is shunted in normal operation. In this case, the output current flows through the diode D_5 in the converter-4. The input of the failed converter will be shunted and converter-4 will be activated if one of the other converters breaks. This redundancy increases the reliability of the current-to-current converter.

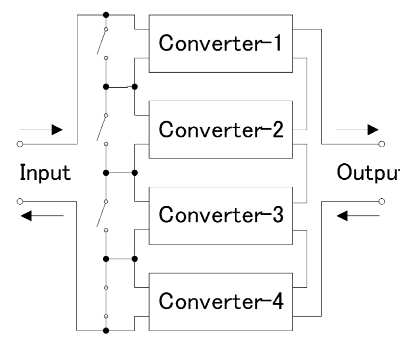

Fig. 4. Connection of plural converters.

III. Comparison Between Experiments and Computer Simulation

A. Simulation Model

To deepen our understanding of the converter, we conducted computer simulations and compared those results with experimental results. The simulation was done using PSpice. Fig. 5 shows the basic circuit used in the simulation.

A linear core model was used for the transformer T_1 because the magnetic flux density in the experiment was much lower than that of the saturation level. In the linear model, a transformer was represented by two inductances, a coupling coefficient, and resistances of windings. Resistances R_1 and R_2 in the primary of the transformer represent the loss in the ferrite core and switching loss of field-effect transistors (FETs).

B. Waveform

Fig. 6 shows a comparison between observed waveforms and simulation results. The upper two waveforms in the figure show

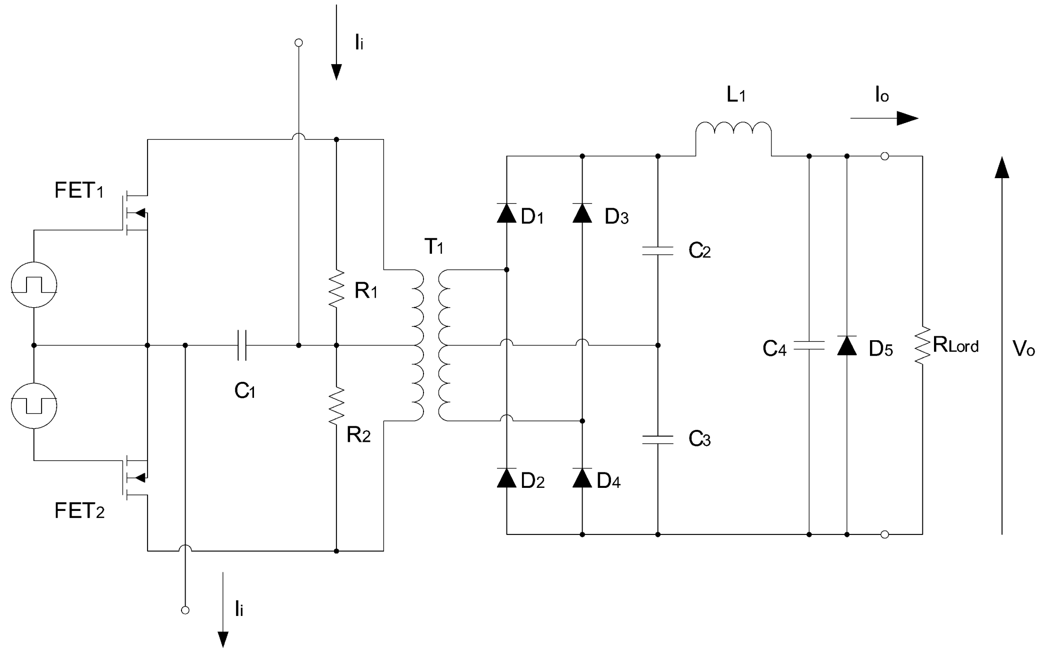

Fig. 5. Basic circuit diagram for the simulation.

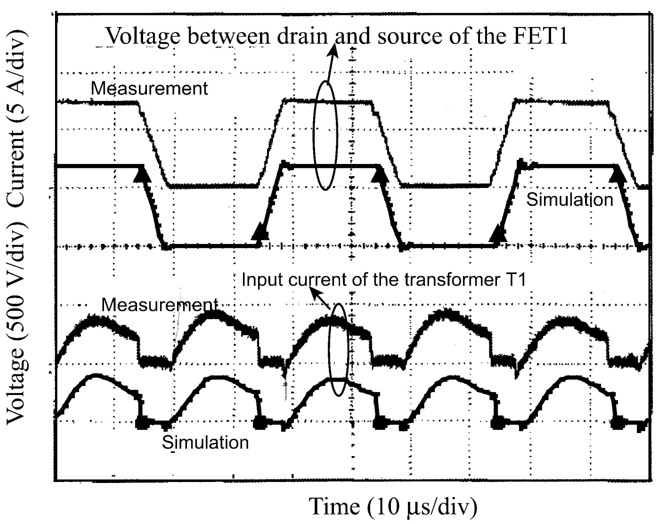

Fig. 6. Comparison of observed waveforms and simulation results.

the source-drain voltage of the FET_1; the lower two waveforms show the current flowing into the transformer.

The coupling coefficient of the transformer was selected as 0.992 so that the calculated current waveform coincided with measured waveforms. This coupling coefficient shows good agreement with the measured value of 0.994.

The simulated waveform coincides well with the measured waveforms, which proves the validity of the simulation.

C. Output Characteristics

We have produced three converters and compared their output characteristics. Fig. 7 shows that the output currents are almost constant regardless of the output voltage; they can be considered as CC sources. The equivalent slope resistance is about 5.6 kΩ. This slope resistance corresponds to the output resistance. The output current should be the same when plural converters are connected in series. Because the converter has finite slope resistance, the output current range has some allowance. This allowance makes it possible to connect plural converters in series. The moderate slope resistance is suitable for the series connection, which renders a very high slope resistance undesirable. The output characteristics of these converters are quite similar, which also facilitates the series connection.

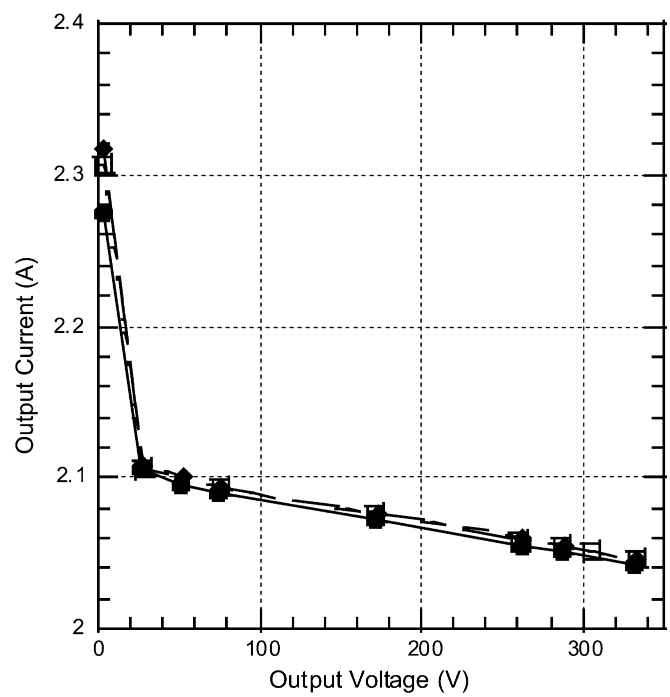

Fig. 7. Output characteristics of the first prototype.

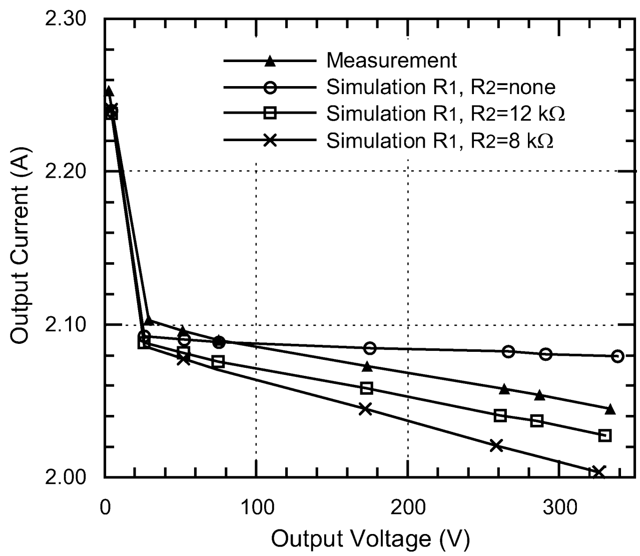

Fig. 8. Influence of deviation of R_1 and R_2 against the output characteristics.

Increase of output current is apparent at regions of lower than 20 V output. It is caused by the intrinsic body diode of MOSFETs. When one MOSFET is switched off, the body diode within the other MOSFET is activated because of the transformer's inductance; the current continues flowing through the circuit of the body diode, transformer, and capacitor C_1. When the output load is heavier and the output voltage is higher, the energy of this current will be absorbed rapidly by the output load and the current will decay. However, if the output voltage is lower and the output load is lighter, the current decay is rather slow. This residual current flowing through the body diode increases the output current in the lower output voltage region.

Fig. 8 shows the simulated and measured output characteristics, where R_1 and R_2 are changed as parameters. The output characteristics with R_1 and R_2 of 12 kΩ coincide well with the measured characteristics; also, the deviation of resistance affects the output characteristics. The output resistance of the converter is approximated as $(R_1 + R_2)/2 = 6$ kΩ, which is almost equal to the measured slope resistance of 5.6 kΩ.

Fig. 9 shows the output characteristics when the on-resistance of FETs (R_{on}) is changed. Because the converter is driven with CC, the deviation of on-resistance of FET does not affect the output characteristic. The deviation of winding resistance of the transformer does not affect the output characteristics for the same reason. However, these resistances degrade the converter efficiency.

Fig. 10 shows output characteristics of the converter when the coupling coefficient of the transformer was changed as a parameter. This figure shows that the deviation of coupling coefficient influences the output characteristic in the lower output voltage region when it is lower than 0.99. Because the measured coupling coefficient of 0.994 is greater than 0.99, practically speaking, its deviation has little influence on the output characteristic.

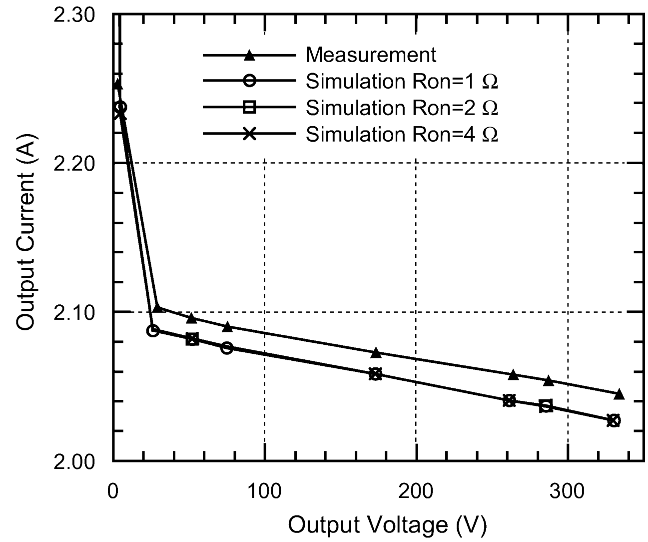

Fig. 9. Influence of on-resistance (R_{on}) of FETs against output characteristics.

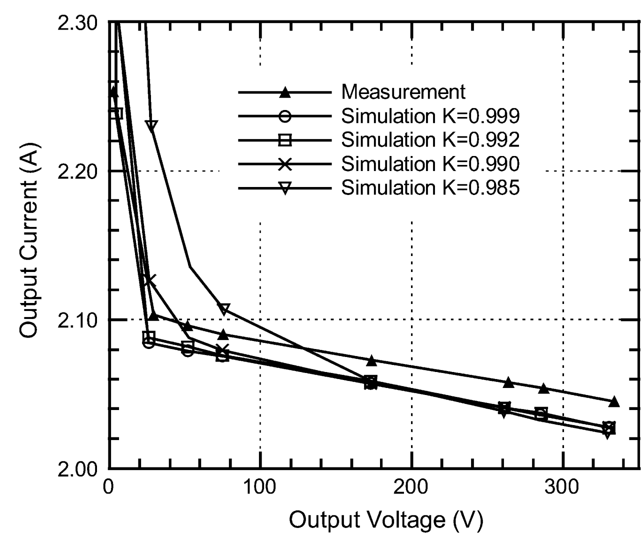

Fig. 10. Influence of the coupling coefficient of the transformer against the output characteristics.

D. *Efficiency*

The converter efficiency is shown in Fig. 11. Neither the power consumed by the drive circuit nor the control circuit is included in this calculation. The simulation and the measurement show good agreement in the higher voltage region, where efficiency of about 95% is obtained. Little difference exists in the lower voltage region.

The calculated breakdown of the loss in the higher voltage region is shown in Table I. Because the loss of the core can be estimated as about 3 W, the switching loss of FET, which is estimated to be about 17.8 W, is dominant.

E. *Temperature Characteristics*

Fig. 12 shows the measured temperature dependence of the output characteristics. The output current and slope resistance are temperature dependent, which is considered to be mainly the result of the transformer's temperature dependence. However, because differences between output characteristics of the three

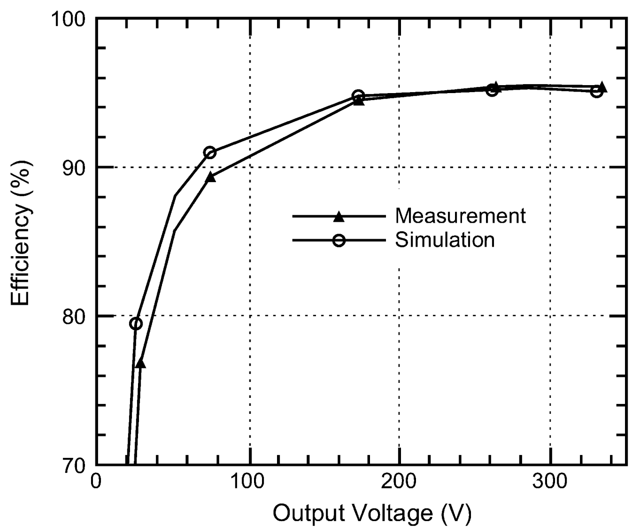

Fig. 11. Efficiency of the first prototype.

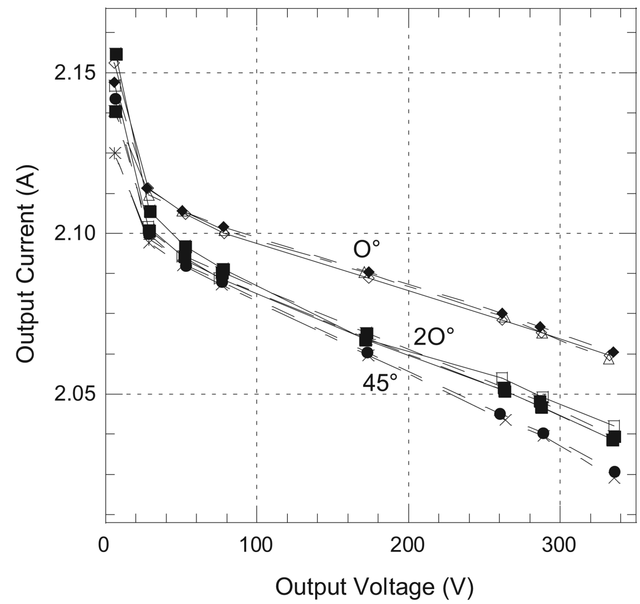

Fig. 12. Temperature dependency of the output characteristics.

TABLE I
DETAILS OF THE LOSS (OUTPUT VOLTAGE: 330 V) R_1 AND R_2, RESPECTIVELY, REPRESENT THE LOSS IN THE CORE AND THE SWITCHING LOSS OF FETS

Item	Loss
On-resistance of FET	6.3 W
Power loss of R_1 and R_2	20.7 W
Diodes D_1, D_2, D_3 and D_4	3.2 W
Resistance of winding wire	1.3 W
Other losses	3.6 W
Total	35.1 W

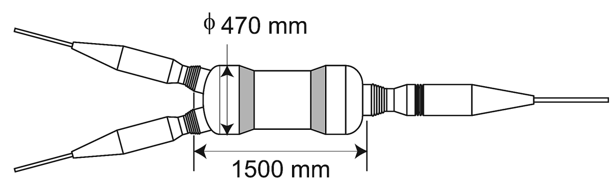

Fig. 13. Typical appearance of BU for optical telecommunication cable systems.

converters are small for all temperatures, they can be connected in series at these temperatures.

IV. COMPACT PROTOTYPE

We have produced a compact second prototype [8] which can be mounted in a branching unit (BU, depicted in Fig. 13) of underwater telecommunication cable systems. We then evaluated its performance. The BU can be deployed to and recovered from 6000-m depth.

A. Basic Specifications

Table II shows the basic specifications of the second prototype. The specifications for voltage and size are applicable to the entire system. Four converters are connected in series to increase the power output. Fig. 14 shows a photograph of the whole system.

The basic circuit of those converters is the same as that of the first prototype.

TABLE II
BASIC SPECIFICATIONS OF THE SECOND PROTOTYPE

Items	Specifications
Max. Input Current	1.4 A
Max. Output Voltage	600 V
Max. Output Current	1.4 A
Number of Converters	4
Switching Frequency	25 kHz
Efficiency	Higher than 90%
Size	375 mm (L) × 200 mm (H) × 200 mm (W)

B. Electrical Characteristics

Fig. 15 shows output characteristics of the whole system in which four converters are connected in series. It can be reconfirmed that the output can be regarded as a CC source. The slope resistance is about 11.5 kΩ in the output voltage range higher than 100 V. The output resistance of a converter is about 2.9 kΩ, which is one-quarter of the slope resistance of the whole system. It is because four converters are connected in series. We think the difference between the slope resistance of the first prototype and that of the second prototype is mainly attributable to

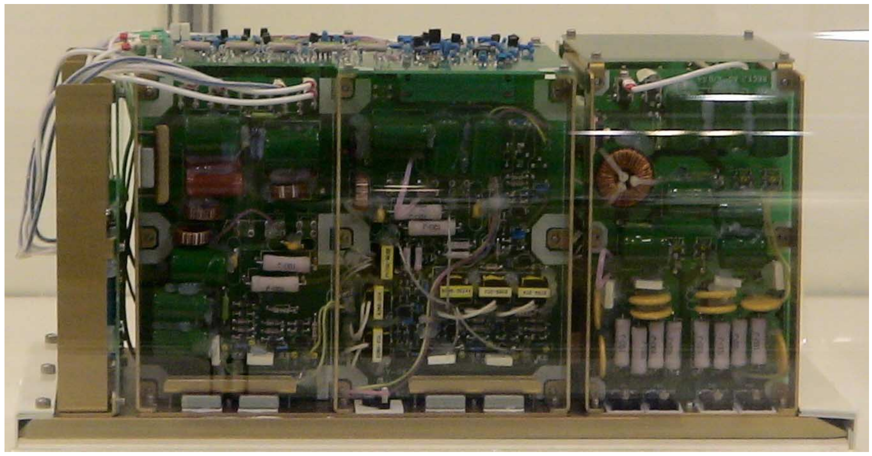

Fig. 14. Photograph of the second prototype.

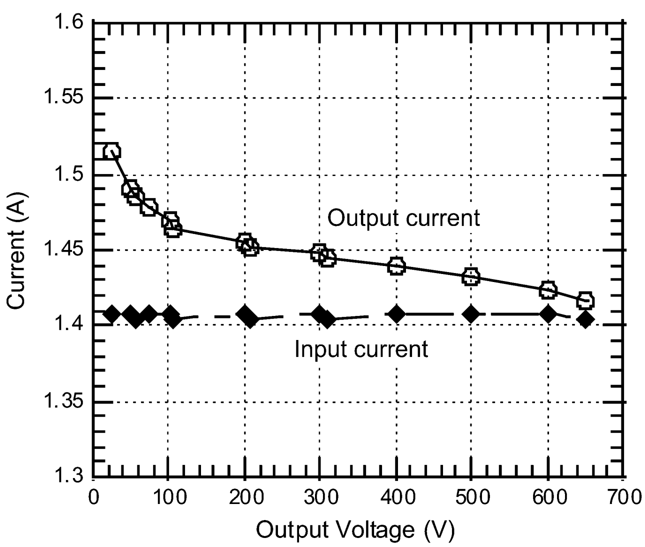

Fig. 15. Output characteristics of the second prototype.

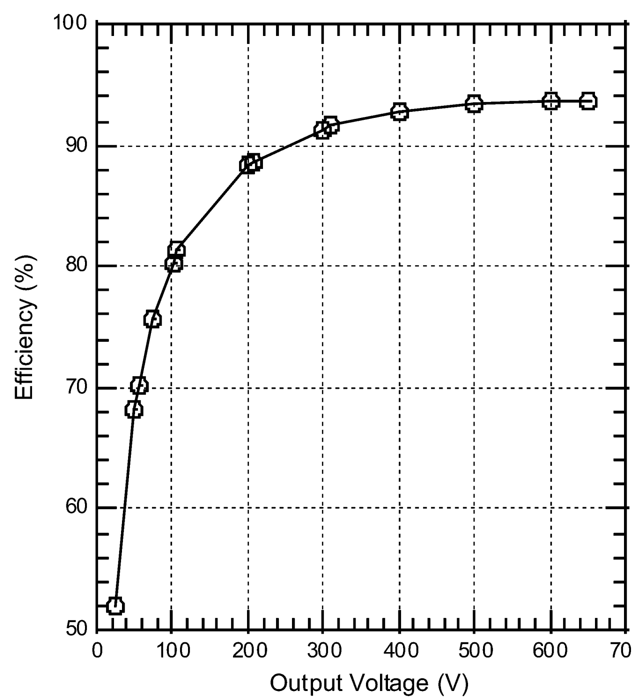

Fig. 16. Efficiency of the second prototype.

the difference between the transformers. We used smaller transformers for the second prototype to reduce the size, which increased losses in the core and decreased the slope resistance.

The converter efficiency is described in Fig. 16. Although the power consumed by the controller is not included in the calculation of the efficiency, high efficiency of about 95% in the higher output range is realized.

All the results described previously concur with those obtained with the first prototype.

C. Heat Dissipation

Heat dissipation is an important issue because the converters are mounted in a watertight housing, the heat dissipation characteristics of which are poor, especially in the air. It also affects the long-term reliability.

Fig. 17 shows results of the experiment of temperature rise with the maximum load. The converters were housed in a rectangular housing, which had almost equivalent heat dissipation characteristics to those of BUs. Fans are not used, thereby increasing the long-term reliability. Seven temperature sensors were attached to each part of the current-to-current converter. Fig. 17 shows that the temperature became stable after about 7 h. Because the temperature rise is less than 23 °C, its effect on long-term reliability is inferred to be negligible. The locations at which the temperature rise was highest were the transformer surface and the top of the circuit board. Because the FETs and diodes are installed directly on the base plate, which has good thermal conductance, the temperature rises of these devices are less than that of the transformer.

V. Conclusion

The CC power-feeding system presents many advantages for scientific underwater cable networks. The authors have proposed a new current-to-current converter, which is a key device to realize mesh-like cable networks with a CC power-feeding system. Because the basic circuit is simple and no feedback loop exists, it is easy to obtain higher reliability.

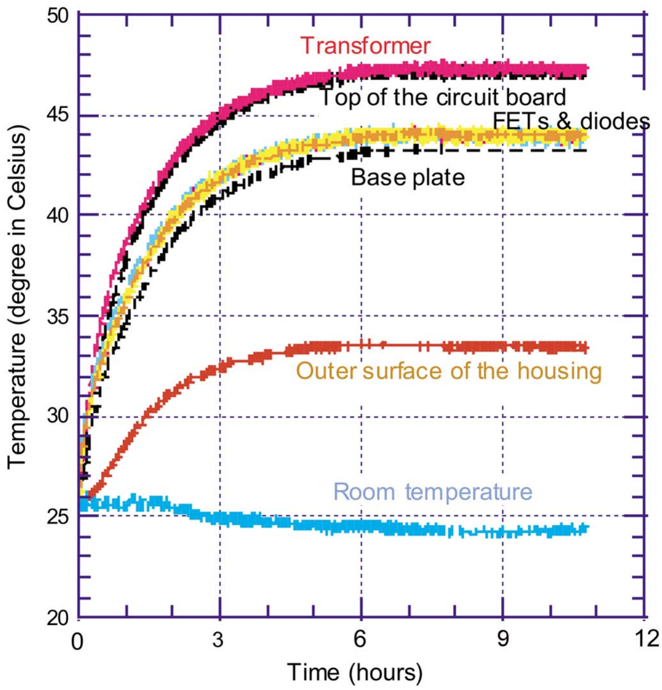

Fig. 17. Results of the experiment of temperature rise with the maximum load.

Two prototypes of the current-to-current converter were developed and evaluated.

Experiments using the first prototype confirmed the following:

1) the proposed current-to-current converter has good characteristics;
2) because the output resistance is sufficiently high, it can be regarded as a current source;
3) the conversion efficiency is higher than 95% in the higher voltage region;
4) the output characteristics of the three converters are sufficiently compatible that they can be connected in series to increase the output power.

The results of the simulation agree well with the experimental results, which proves the validity of the simulation. The simulation showed the following:

1) the loss in the ferrite core and the switching loss of FETs have dominant influence on output characteristics;
2) on the other hand, on-resistance of FET and the coupling coefficient exert little influence on output characteristics.

A temperature rise test was conducted using the second prototype. In that test, the current-to-current converter was placed in a rectangular housing that had thermal properties that were almost equivalent to those of BUs. Results confirmed that the temperature rise was sufficiently low that its effects on long-term reliability were negligible.

These results show that the proposed current-to-current converter has promising features. It will provide great benefits for the design and construction of scientific underwater cable networks.

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