A Technical Report on the Advanced Real-time Earth Monitoring Network in the Area

Chapter 3: Power feeding System
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Contents

3.1 Introduction

In a optical underwater telecommunication cable system, a constant-current (CC) power feeding system is adopted to supply power to underwater repeaters inserted in the cable. As there is only a single power feeding line in the cable, seawater is used as the return path for the currents.

CC power feeding system has advantages that it can continue power feeding even in the event of a shunt fault in the cable, as long as power feeding equipments (PFE) are placed at both ends of the cable, since such a fault would only bring the electric potential at the fault location to a level equal to ground potential. It also has the following benefits: power can easily be made available in an underwater repeater by inserting a Zener diode in the power feeding line; and the electronic circuit of an underwater repeater can easily be insulated from seawater by covering the entire circuit with an insulator as its electric potential is almost equal to that of the power feeding line. These advantages explain why underwater telecommunication cable systems use the CC power feeding system.

However, ARENA will be completely different from conventional underwater telecommunication cable networks in that it is envisioned to have a mesh-like network delineated by two cables laid on both sides of the Japan Trench, as discussed in **Chapter 2**. Since current branching is not easy under the CC power feeding system, it was not easy to apply the conventional CC power feeding system for ARENA. For this reason, the following alternative power feeding systems are proposed and compared in this chapter: (a) constant-voltage (CV) power feeding system[(1)-(5)]; (b) CV/CC hybrid power feeding system, which combines CV power feeding system and CC power feeding system; and (c) CC/CC power feeding, in which a CC is produced from another CC[(6)-(8)]. The three systems are cross-compared on the basis of the cable network model proposed in **Chapter 2**.

Before comparative studies begin, technical requirements must be clarified. For this reason, basic system requirements are specified in **Section 3.2**.

Apart from CV, CC and CV/CC power feeding system as mentioned above, power feeding systems can also be classified into DC power feeding system and AC power feeding system. AC power feeding is examined in **Section 3.3**, demonstrating that it is not suitable for ARENA due to large power loss. Therefore, **Section 3.4** and subsequent sections concentrate on DC power feeding.

In the feasibility study, a new CC to CC converter (CC/CC converter) was proposed that converted a CC to another CC. The CC/CC converter was a key device for CC/CC power feeding system. Preliminary experiments using the prototype of the CC/CC converter and computer simulation was carried out[(8)], and the results show a promising feature of the CC/CC converter.

Consideration and the some preliminary results of experiment and computer simulation on CV, CC and CV/CC power feeding systems are described in **Sections 3.4** to **3.6**. As a result of such comprehensive examinations and comparison shown in **Section 3.7**, the CC/CC power feeding system is thought to be most promising under the given conditions.

3.2 Technical requirements for power feeding system

The technical requirements for the power feeding system are shown below.

(1) Required power

Table 3-1 shows the number of observatories, along with their power consumption (see **Chapter 2** for details). The total number of nodes is 66. Each node has two geophysical observatories. The power consumption figures given in **Table 3-1** represent minimum power consumption currently estimated, and are therefore subject to review in the course of the actual planning of the cable system.

Table 3-1 Types and Number of Observation Points and Estimated Power Consumptions

	Average power consumption (W)	Number of observation points	Subtotal (W)
Geophysical observatory	15	132	1,980
Borehole observatory	69	2	138
Oceanographic observatory	121	10	1,210
Geodetic observatory	11	43	437
Optical sensor array	4	2	8
Camera observation	212	2	424
AUV station	60	10	600
Accoustic tomography	60	4	240
Optical data transmission system	200	66	13,200
Total			18,273
Average			277

(2) Power feeding line

The structure of the underwater cable has a major impact on the power feeding system. Optical underwater telecommunication cables are made for installation at depths of up to 8000 m, as well as being retrievable for repairs. They are also designed to withstand large forces that may be encountered during burial under the ocean floor in shallow sea. Moreover, in addition to long-term reliability and economy, numerous technical and economic requirements are taken into consideration, including measures to prevent rapid water intrusion in the event of a fault, reliable feedthroughs and mechanical couplings for repeaters, and jointing techniques to be used during repairs. Scientific submarine cables are subject to similar performance requirements. In this regard, developing a custom-made scientific submarine cable, which meets all these conditions but has a different structure from an optical underwater telecommunication cable, would require an enormous development outlay and a development period of up to several years. For this reason, it would be appropriate to use an optical underwater telecommunication cable for ARENA.

Optical underwater telecommunication cables have a single power feeding line and use seawater as the return path for the currents. This presents a major constraint for the selection of a power feeding system for a scientific cable network.

(3) Reliability

Since a fault occurring in the power feeding system would greatly affect the overall operation of the system, it must have high reliability. This is particularly true of built-in underwater power supplies as underwater devices are not easy to be repaired or be replaced. For this reason, underwater telecommunication cable systems are designed to conform to a failure rate of no more than a few failures throughout their design life, which is over 20 years. However, it is not realistic to expect a similar level of reliability from all built-in underwater power supplies due to the greater complexity of the power feeding system and larger number of components. This gives rise to the need to find other ways of increasing the reliability of the system as a whole, including the introduction of backup arrangements for underwater power supplies, so as to minimize the affected range by faults occurring in the power feeding system.

(4) Cost

Cost and reliability are mutually exclusive. While components designed for space applications or underwater telecommunication cable systems have high reliability, they are also expensive. Moreover, they are limited in choice. Custom-made components with high reliability are not much better, because they would result in enormous development costs. For these reasons, the use of general-purpose components should be pursued, accompanied by efforts to enhance the reliability of the system as a whole through, for example, greater redundancy.

(5) Expandability

It is more realistic to build the envisaged large-scale scientific cable network in stages over several years than trying to complete it all at once. For this reason, the cable network is required to be dividable into segments and operable on a segment by segment basis, as well as being easily expandable.

(6) Measures against cable shunt fault

Since the power feeding line incorporated into an unarmored deep-sea optical submarine cable is only protected by a polyethylene layer, there are sometimes shunt fault of the power feeding line due to the break of the polyethylene layer. It is therefore necessary to make a provision to minimize the affected range by such a fault and ensure power feeding to unaffected sections.

(7) Onboard handling

It is envisaged to use a cable ship capable of simultaneously handling two cables when deploying power branching units (PBUs). The size and weight of the PBU need to be within the capability of such a cable ship. If a fault occurs in a PBU, it will have to be retrieved onto the cable ship. The sizes and weights of built-in power supplies for the node branching unit (NBU) and the underwater hub unit (UHU) also need to be limited in consideration of handling on the cable ship.

(8) Surge protection

When an shunt fault occurs to a cable, a large surge current/voltage is generated in it. For example, where the electric potential of the cable is 8 kV and its characteristic impudence is 40 Ω, the surge current will reach 200 A. The power feeding system must be able to withstand such surge currents and voltages.

(9) Electroding (EL) - superimposition of low frequency AC current on feeder current

ROVs are used for the burial of cables and maintenance. When an ROV follows the cable, a technique to guide it by superimposing a low-frequency AC current on the current and generating a low-frequency magnetic field is being widely used. PFEs at landing stations and PBUs must support such an EL function.

(10) Efficiency and heat dissipation

From the viewpoint of reliability, the use of a cooling fan for the power supply in an NBU and PBU is considered difficult. For this reason, devising an efficient heat sink is a major technical task. To alleviate the heat problem, it is also important to increase equipment efficiency and reduce heat consumption.

(11) Response to load fluctuations

There are two types of load fluctuation.

The first arises from large pulse outputs generated by acoustic tomography and other loads. To handle this type of load fluctuation, the use of a secondary battery or large-capacity electric double-layer capacitor may be considered. This issue needs to be examined from various aspects, including the long-term reliability of such devices.

The second arises from the addition/removal of sensors or nodes. Power supplies must be able to accommodate such load fluctuations.

3.3 AC power feeding system

For land-based power grid, the AC CV power feeding system is widely used. AC power feeding is very advantageous in terms of the ease of voltage change via a transformer. It is examined here focusing on its power transmission efficiency.

Although the use of a optical underwater telecommunication cable is recommended in system requirement (2) above, the examination covers the use of a stranded-wire submarine power cable as well.

3.3.1 AC power feeding using optical underwater telecommunication cable

In the case of an optical underwater telecommunication cable, power feeding is achieved through the use of a single-conductor power feeding line built into the cable, with seawater used as the return path for the currents. Under those conditions, the propagation constant, γ, is given by the following formula:

$$\gamma = \sqrt{j\omega C_0 (R_0 + j\omega L_0)} \quad \textbf{(1)}$$

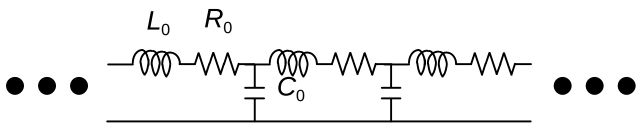


Figure 3-1 Equivalent circuit of optical underwater telecommunication cable

where

R_0: DC resistance per unit length (Ω/m)
L_0: Inductance per unit length (H/m)
C_0: Capacitance per unit length between power feeding line and seawater (F/m)

An equivalent circuit for the submarine is shown in **Figure 3-1**. Since $\omega L_0 \ll R_0$, formula **(1)** can be approximated as follows:

$$\gamma = \sqrt{j\omega C_0 R_0} = (1+j)\sqrt{\frac{\omega C_0 R_0}{2}} \quad \textbf{(2)}$$

Transmission loss, η, is given as:

$$\eta = 20\sqrt{\frac{\omega C_0 R_0}{2}}\log(e) \ (\mathrm{dB/m}) \quad \textbf{(3)}$$

Substituting $C_0 = 1.44 * 10^{-10}$ F/m and $R_0 = 7.2*10^{-4}$ (Ω/m) as in the case of the OS optical underwater telecommunication cable, transmission loss is calculated as follows:

-4.9 dB/1,000 km at 1 Hz
-17 dB/1,000 km at 10 Hz
-38 dB/1,000 km at 50 Hz

Thus, unless the frequency is lowered below 1 Hz, transmission loss will be too large. However, since such a low frequency makes transformers far too large, AC power feeding is unrealistic.

3.3.2 AC power feeding using stranded-wire submarine power cable

In the power industry, submarine power cables incorporating optical fibers are widely used for power transmission to remote islands. For this reason, AC power feeding based on a stranded-wire submarine power cable is now examined.

Taking the submarine power cable “22 kV CV 3 x 60SQ” from Hitachi Cable, Ltd. as an example, transmission loss is calculated. The cable has the following primary constants.

Ro=0.397 Ω/km
Lo=384mH/km
1/Go=30,600 Ω・km
Co=0.183 μ F/km

Applying these values, transmission loss at the commercial frequency (50 Hz) is calculated as follows:

35.5 dB/1,000 km

This is similar to the figure obtained from an optical underwater telecommunication cable, and is therefore unrealistic.

3.4 Constant-voltage power feeding system

The greatest advantage of the CV power feeding system (**Figure 3-2**) is easy to branch electric power. However, it poses a problem in that a shunt fault occurring in the cable would cause the system voltage to fall and affect the operation of the system as a whole, unless some kind of preventive measure is taken. Therefore, an effective measure for shunt faults in the cable is an important issue regarding the CV power feeding system.

At each observation node, a low voltage CV source needs to be regulated from a high-voltage DC power source. A shunt fault occurring in the CV source in a node would also cause the system voltage to fall, thus affecting the operation of other nodes. To minimize the impact of this type of fault, it is necessary to automatically disconnect the CV source in the faulty node from the power feeding line. If a shunt fault occurs in the power feeding line, the affected section needs to be electrically disconnected from the rest of the system. Regarding the restoration of power feeding after a shutdown due to a fault, functions to reconnect the disconnected section - and disconnect it again if necessary - upon a command will also be needed.

Figure 3-3 is an example of the configuration of a power system in NBU that would meet those requirements(3). In this example, the power supply unit is duplicated to increase its overall reliability. If either of the power supply units is shunt faulted, latch relay Rly1a or Rly1b, as the case may be, will operate to disconnect it from the power feeding line.

In the event of a shunt fault in the cable, relay Rly2a or Rly2b will operate to disconnect the failed line. For example, if the right-hand line is shunt faulted, the fault current will flow through Rly2b and diode D2a. This current activates Rly2b and disconnects the right-hand line. In this case, Rly2a is prevented from operating by diode D2a. Power feeding to the node continues via the left-hand line and diode D2a. If the left-hand line is shunt faulted, that line will be disconnected as a result of the operation of Rly2a. Resistances R1a and R1b are designed to adjust the sensitivity of Rly2a and Rly2b. This adjustment makes it possible to activate the relay closest to the location of the fault. Namely, the sensitivity of Rly2b is gradually increased from the left-most node to the right-most node, while that of Rly2a is gradually increased from the right-most node to the left-most node. When a shunt fault occurs in power feeding line, the appropriate relay will operate at both sides of the fault point to electrically disconnect it, thus ensuring power feeding to all nodes. In an ideal case, only the relays closest to the fault point will operate, but relay operation may also occur at adjoining nodes due to deviation in the sensitivity or operating time of individual relays. To deal with such maloperation, latch relays Rly2a and Rly2b need to be reclosable on command from land. An insulation testing function also needs to be incorporated to enable an

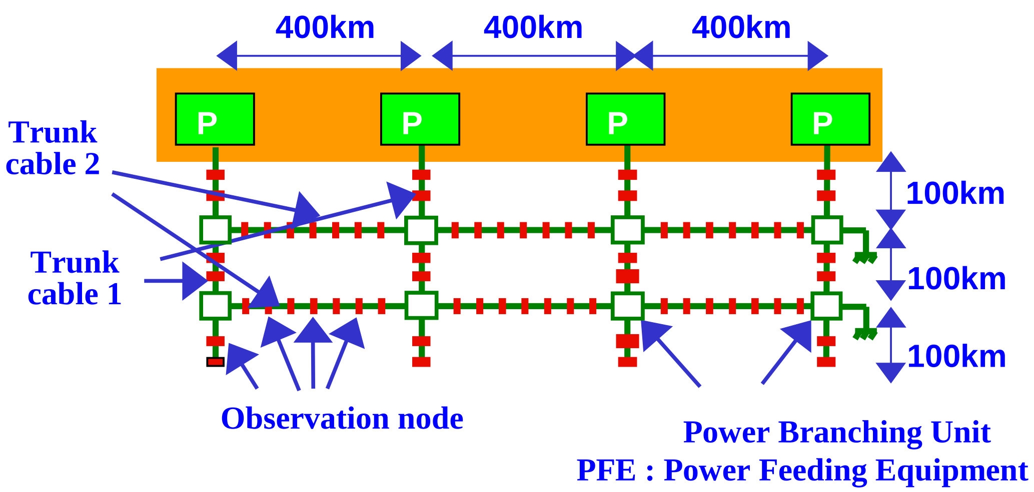


Figure 3-2 Constant Voltage Power feeding system

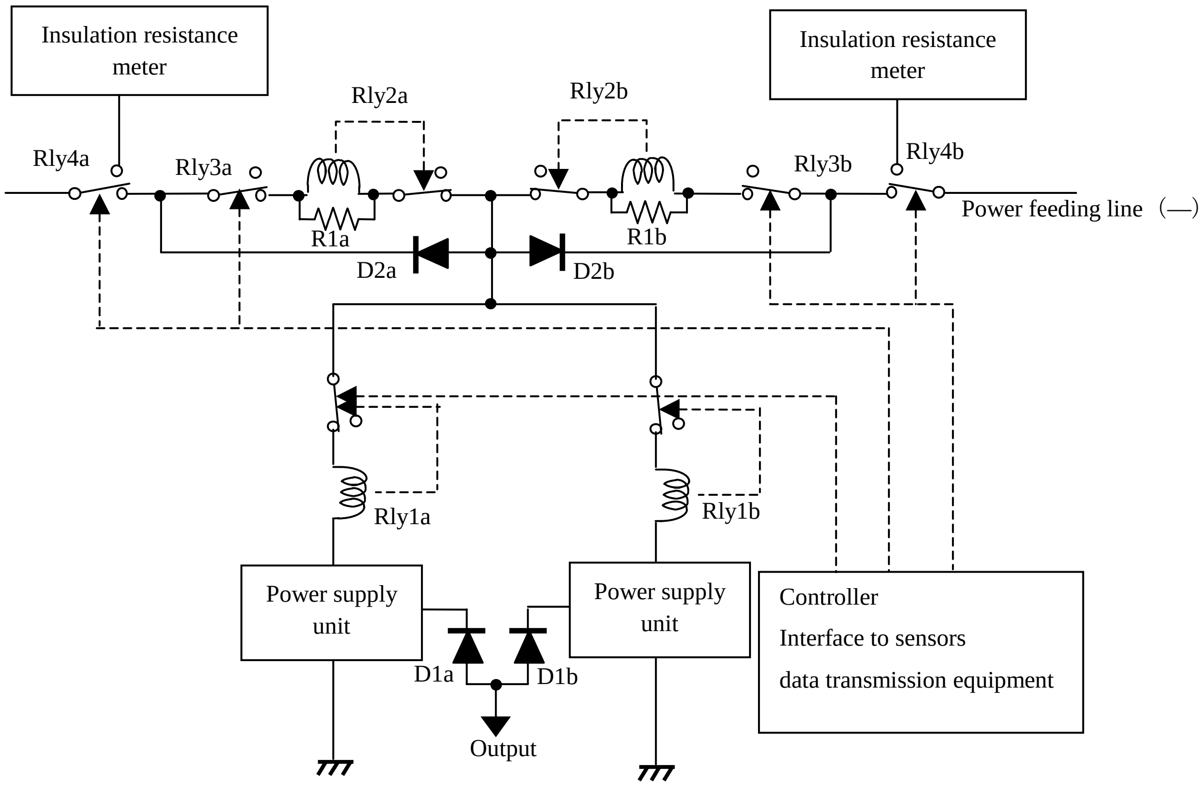


Figure 3-3 Configuration of built-in power system of NBU under constant voltage power feeding system

insulation check prior to the reconnection of the left- and right-hand-side lines, respectively.

In this regard, Kirkham et al.[(1),(2)] propose the following protection measures for the CV power feeding system: a network protection system based on a high-speed network; and a system that controls circuit breakers based on the calculated distances to the fault. Schneider et al.[(4)] propose a cable fault protection method in which circuit breakers are switched back on one by one after a fault, starting with the node closest to the landing station. Before each circuit breaker is turned on, the adjoining power feeding section is checked for a fault through resistance measurement.

Figure 3-4 shows the configuration of the power supply unit in NBU for CV power feeding system. Assuming the use of a MOSFET switching device, it seems difficult to make a DC/DC converter with an input voltage of several kV due to the voltage limit of the MOSFET - unless multiple converter units (n stages) are used in such a way that their input circuits are connected in series to share the input voltages, as shown in **Figure 3-4**. Otherwise, the development of a special DC/DC converter using a high-power thyristor, etc. will be needed. The method shown in **Figure 3-4** requires the input voltage to be divided equally among individual converter units. In the VENUS system, a power supply unit for CC sources with multiple converters connected in series was developed.

To prepare for faults in converter units, relays that bypass their input currents must be provided. The number of converter units needs to be determined by taking into consideration the maximum rating of the available switching device, its efficiency, dimensions, etc. Since the output circuits of converter units are connected in parallel, faults in some converter units will not result in a drop in output voltage. It is possible to expand the range of allowable input voltages by adding a control circuit that only activates one or two converter units during low input voltage stage. (In **Figure 3-4**, the nth converter unit is not provided with a relay, allowing it to operate during low input voltage stage (= start-up). During start-up, other converter inputs are shunted using bypass relays.) Such a function is particularly beneficial to prevent excess rush current during start-up operation.

The configurations of power supplies and fault protection methods proposed above have never been tried, so that it is necessary to conduct further studies on their operation, reliability, equipment size, heat dissipation, etc. Apart from MOSFET, the use of other switching devices such as IGBT, GTO, etc. needs to be considered.

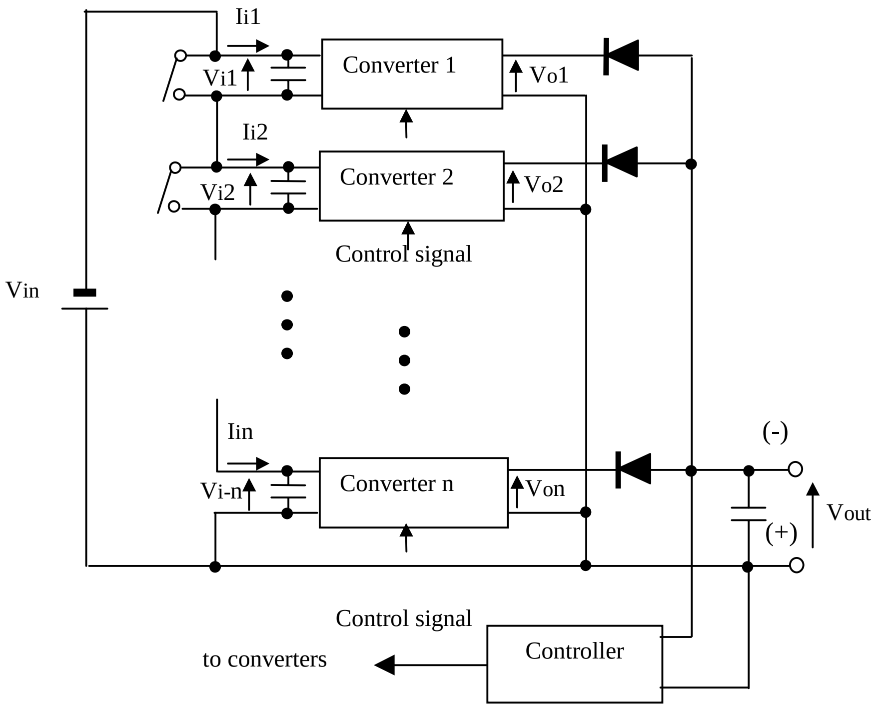


Figure 3-4 Power supply unit in NBU

Figure 3-5 shows a configuration of a PBU. In the event of a shunt fault, the cable section in which an overcurrent has been detected is electrically disconnected from the other section using a latch relay. Such a latch relay must be reclosable on command. The PBU incorporates a function to measure the resistance and insulation resistance of the disconnected power feeding line to locate the fault. The interconnection of trunks 1 and 2 via a diode, ensures that power feeding to trunk 2 continues via the adjoining PBU even if an shunt fault occurs in the PFE or trunk 1.

Finally, let us calculate the supply voltage and current in the event of powering the entire system using the left-most PFE in **Figure 3-2** as a result of faults in the remaining three PFEs. In this case, a total of 48 nodes **-** 42 located on trunks 2a and 2b and six located on trunk 1a, which is connected to the left-most PFE **-** would need to be supplied. Assuming the power consumption at each observation node, electrical resistance of the trunk cable and output voltage of the PFE to be 356 W (at a power supply output of 277 W and a power supply efficiency of 0.85), 0.7 Ω/km and 3,948 V, respectively, the output current of the PFE will be 6.16 A, with the voltage at the observation point farthest from the PFE to be 2kV.

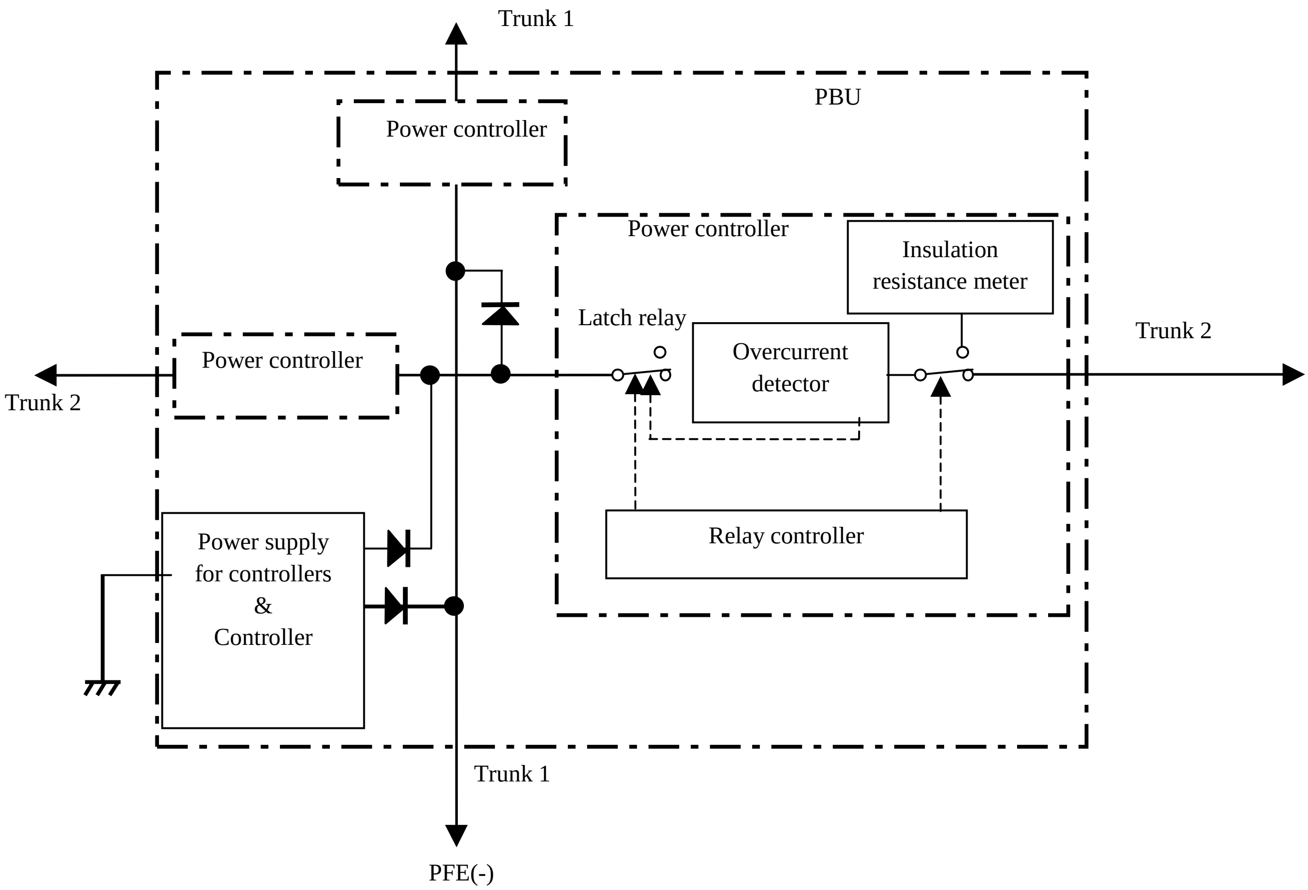


Figure 3-5 Configuration of built-in power controllers in PBU
under constant voltage power feeding system

3.5 Constant-voltage/constant-current hybrid power feeding system

The configuration of the CV/CC hybrid power feeding system, which combines the features of CC power supply and CV power supply, is shown in **Figure 3-6**.

In the CV/CC hybrid power feeding system, trunk 1 is supplied with CV, while trunk 2 is supplied with CC, via PBUs placed at the intersections of trunks 1 and 2. This system brings together the advantages of the CV power feeding system, ease of power branching, and those of the CC power feeding system, relative robustness to cable faults and ease of insulating electronic circuits from seawater.

An example configuration of the PBU is shown in **Figure 3-7**. In this example, a single PBU accommodates two CV/CC converters that supply the rightward and the leftward sections of trunk 2. Two converters can be housed in a single or in two separate units. In this case, one of the output terminals of each CV/CC converter is brought to sea ground. To deal with cable faults, etc., a provision is needed to disconnect the faulted cable section through the operation of switches S1, S2 and S3 on control command.

In this system, a faulty PBU is backed up by adjoining PBUs. For example, when PBUb1 failed in **Figure 3-6**, power supply to trunks 2a and 2b continues via PBUa1 and PBUc1. In this case, the current flowing through PBUb1 is bypassed by the diodes connected in parallel to the CV/CC converters. Assuming the power consumption at a node, electrical resistance of the cable and value of the CC to be 404 W (at an efficiency of 0.75), 0.7 Ω/km and 1 A, respectively, the power output of the PBU is calculated as shown below.

(1) Power output of PBUc1 in normal case (also applicable to other PBUs)

Number of nodes to be supplied	3.5 on each side
Power consumption	404 W * 7 = 2828 W
Power loss in cable	2 * 200 km (one side) * 0.7 Ω/km * $(1\ \text{A})^2$ = 280 W

The total power output is about 3.1 kW (output voltage 3.1 kV).
The input power is about 3.65 kW, assuming an efficiency of 85% (input voltage 3.65 kV).

(2) Power output of PBUc1 in case of fault in PBUb1

Number of nodes to be supplied	10.5
Power consumption	404 W * 10 = 4040 W

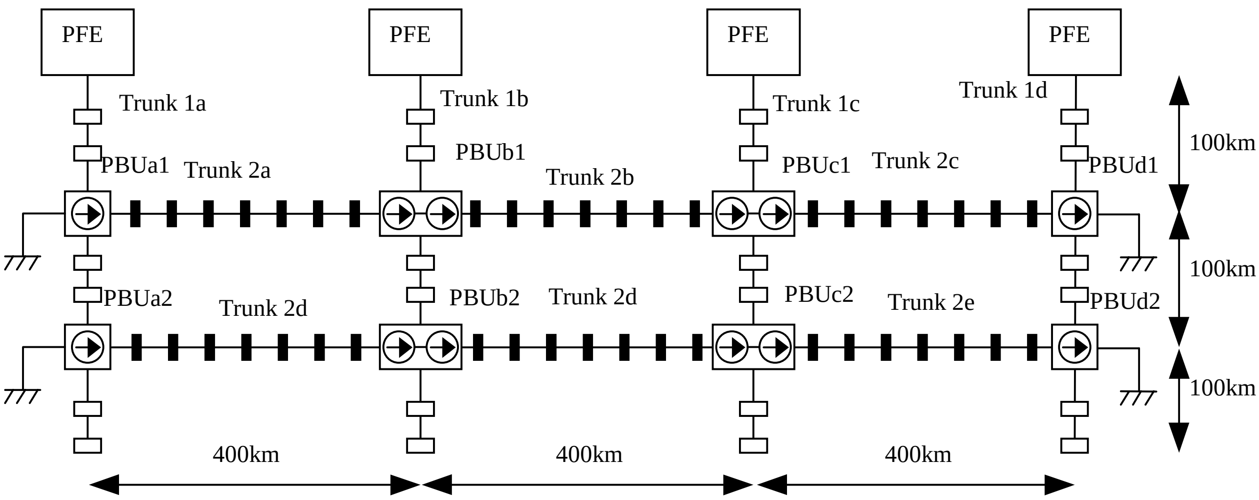


Figure 3-6 Configuration of constant voltage/constant current hybrid system
Trunk 2 is supplied using the constant current power feeding system via PBUs placed at the intersections of trunks 1 and 2. Trunk 1, on the other hand, is supplied using the constant voltage power feeding system.

Power loss in cable 600 km * 0.7 Ω/km * $(1\ \text{A})^2$ = 420 W
The total power output is about 4.46 kW (output voltage 4.46 kV).
The input power is about 5.25 kW, assuming an efficiency of 85% (input voltage 5.25 kV).

Assuming an efficiency of 0.85, as much as 0.79 kW of heat is generated in PBUb1 in the case of a fault. It is therefore necessary to investigate the issue of heat generation and dissipation. One way of alleviating this problem is to reduce total power consumption by turning off observation instruments, except for the main ones such as seismometers.

Let us now estimate the size and weight of the underwater CC source. Assuming a maximum power output of 4.46 kW and a power/volume ratio of 18 W/L by taking into consideration actual figures obtained from existing underwater power supplies and allowances, the volume is estimated to be 248 liters. Assuming a cylindrical shape with an inside diameter of 390 mm, its length (inside dimension) will be 2080 mm.

Although this system combines the advantages of CV power feeding and CC power feeding, the development cost is likely to be high due to the need to develop two types of power supplies for nodes, one for CV power feeding system and the other for CC power feeding system. Another problem is a large maintenance burden.

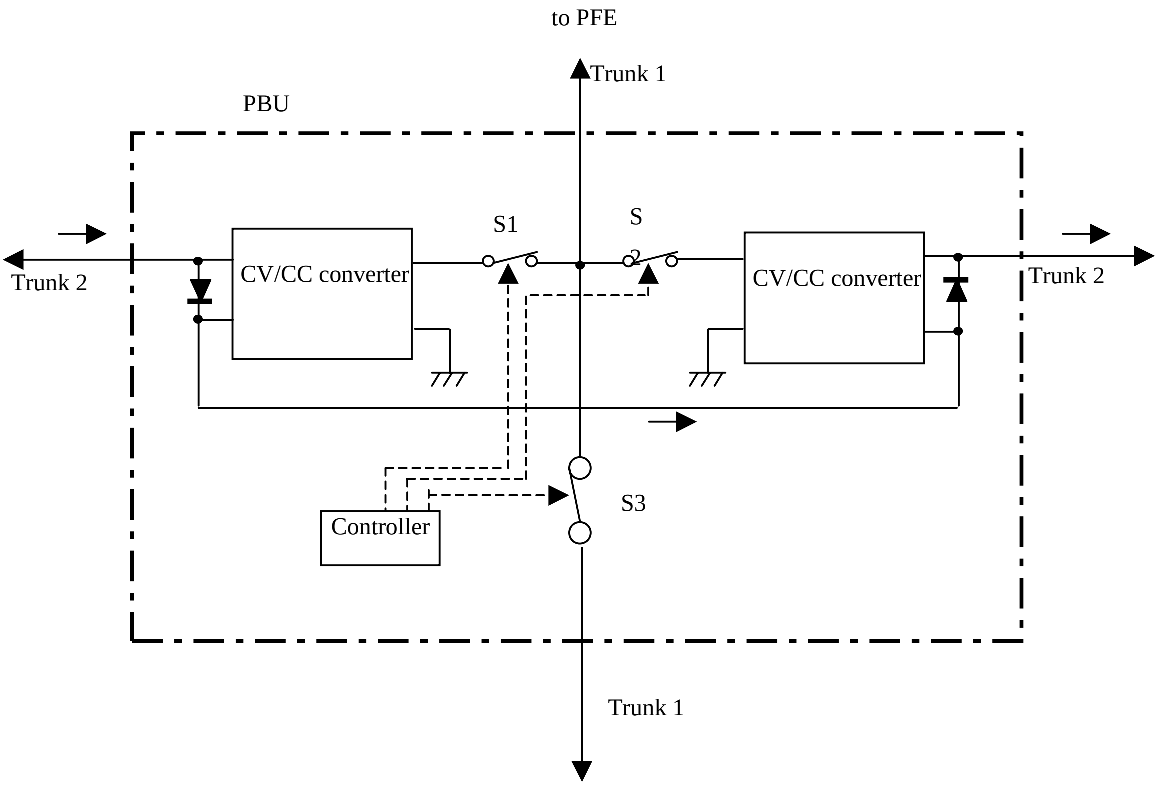


Figure 3-7 Basic configuration of PBU under constant voltage/constant

3.6 Constant-current/constant-current power feeding system

3.6.1 Basic characteristics of Constant-current/constant-current power feeding system

In the CC power feeding system, two CC sources are usually placed at the both end of a cable. The CC source can be schematically depicted with an ideal CC source, output admittance and voltage limiter as in **Figure 3-8**. The output admittance plays an important role to keep the balance between the outputs of two CC sources.

Figure 3-9 explains the operation concept of the CC sources placed at the both end of the cable. The output voltage is limited to prevent overloading. Although the output current of an ideal CC source is constant irrespective of the output voltage in the CC region (the constant current region where output voltage is below maximum output voltage), an output admittance gives the output current a slight output voltage dependence, which is represented by the slope resistance $R_{out} = dV_{out}/dI_{out}$. As there are tow CC source, we can suppose a

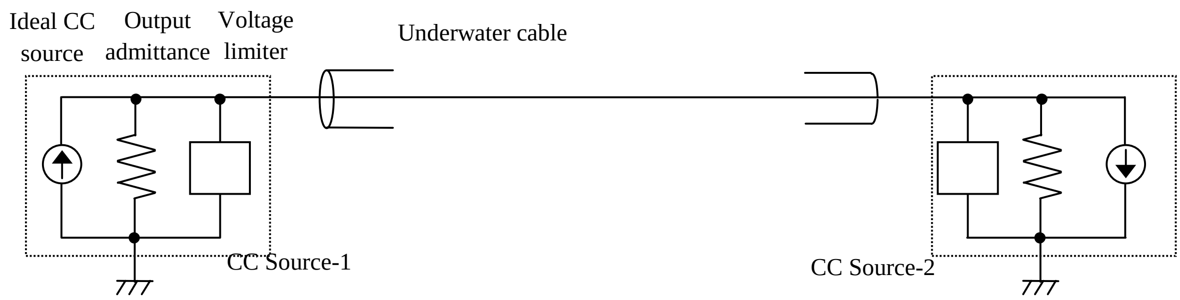


Figure 3-8 Placement of CC sources in CC power feeding system

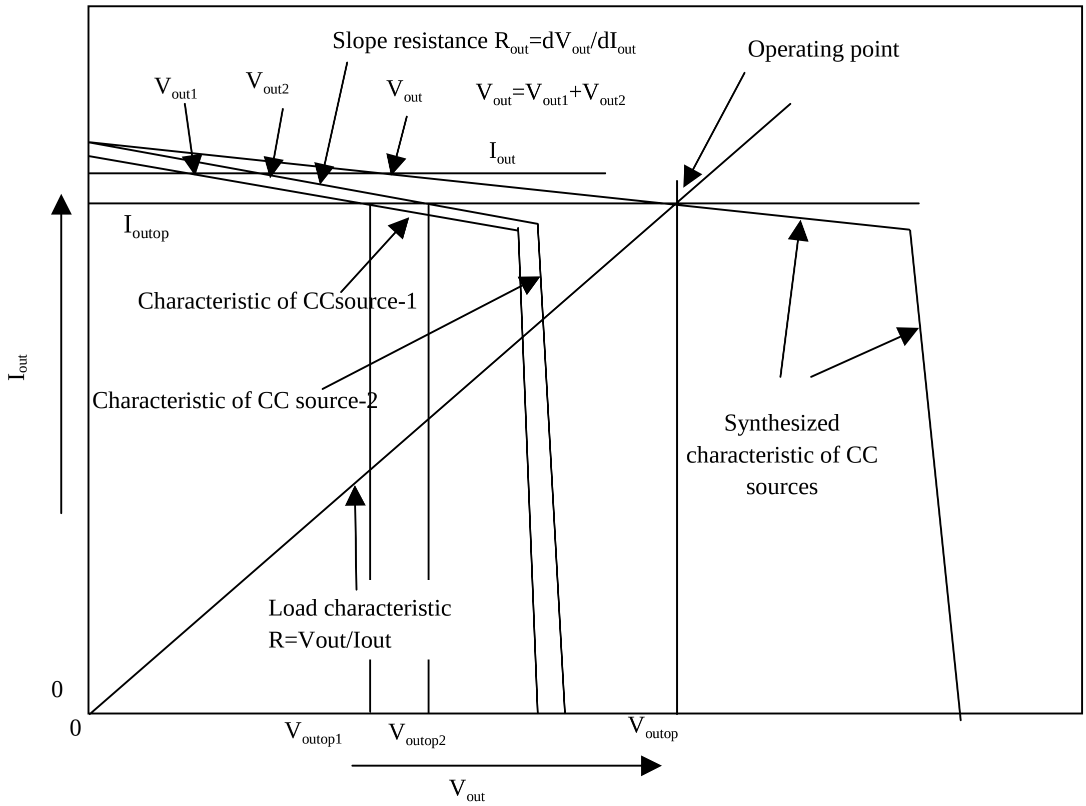


Figure 3-9 Output characteristics of CC sources

synthesized CC source as depicted in **Figure 3-9**. The output voltage of the synthesized CC source V_{out} is equal to the sum of the output voltage of CC source-1 (V_{out1}) and the output voltage of CC source-2 (V_{out2}).

$$V_{outT}(I_{out}) = V_{out1}(I_{out}) + V_{out2}(I_{out}) \quad (9)$$

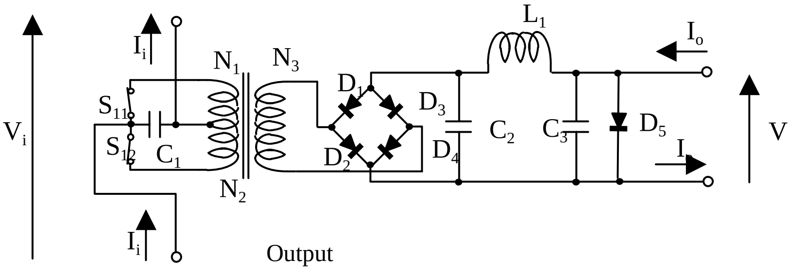


Figure 3-10 Basic electric circuit of the CC/CC converter

Assuming the load of the CC sources is a pure resistance R, the operating current and voltage can be determined by finding the intersection of the synthesized characteristic of the synthesized CC source and the load characteristic. Given the operating voltages of CC source-1 and CC source-2 to be V_{outop1} and V_{outop2}, the synthesized operating voltage is expressed as $V_{outop} = V_{outop1} + V_{outop2}$. It is clear that the right slope resistances are needed to make the two CC sources share the output power and operate as a CC source.

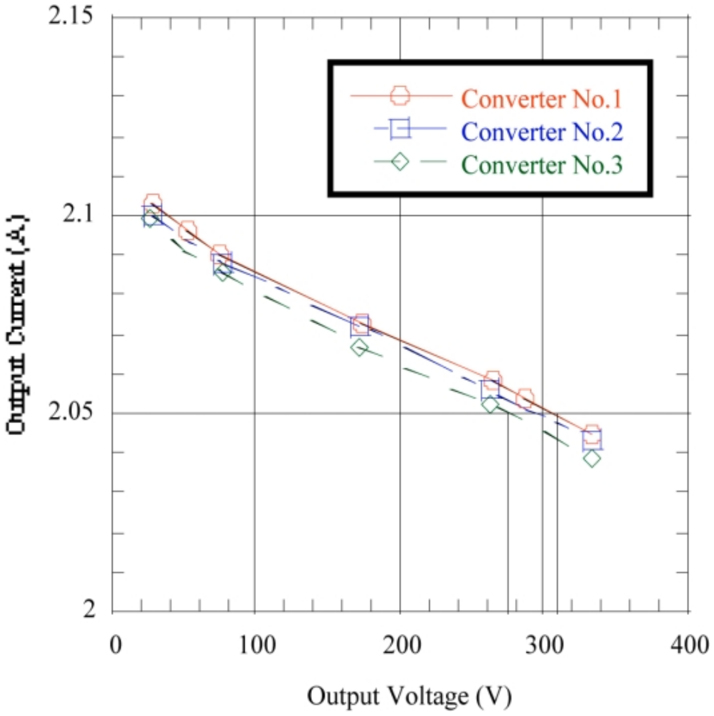


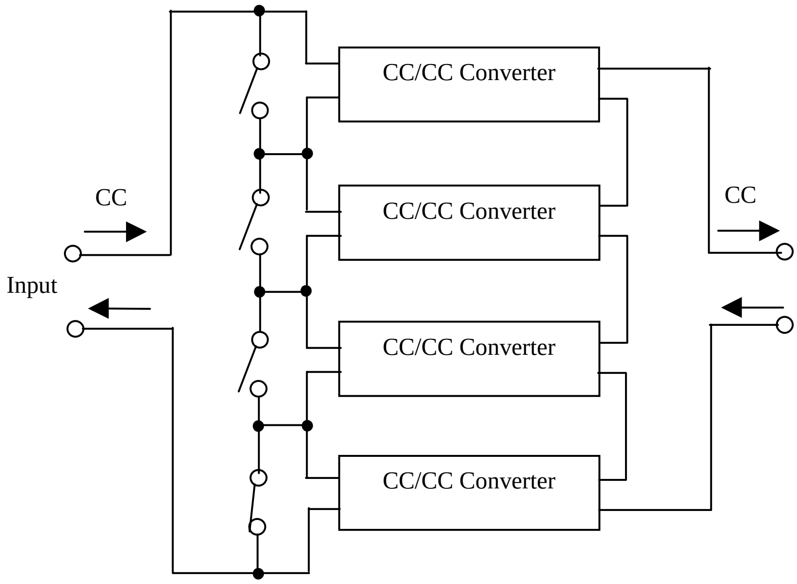
Figure 3-11 The output characteristics of the thee prototype of the CC/CC converter

3.6.2 Constant-current to constant-current converter

In the CC/CC power feeding system, a constant-current flowing in trunk2 is generated from the constant-current flowing in trunk1 using a CC/CC converter put in the PBU.

Figure3-10 shows the proposed basic circuit of the CC/CC converter. The input dc constant current is switched with switching devices FET1 and FET2, and fed into the transformer. The output of the transformer is rectified and filtered. The level of the input current and number of windings of the transformer determine the level of the output current. As this basic circuit is very simple and there is no feedback loop, high reliability and high conversion efficiency can be expected. However there are following basic issues to be considered.

(1) The reliability of the switching device.
(2) Is it possible to connect plural current to current converters in series to increase the output power?
(3) Is it possible to start up power feeding without making excess inrush current?
(4) Is it small and does it have high conversion efficiency so as to be put in a pressure tight housing.



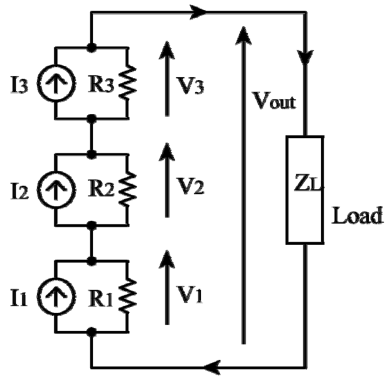


Figure 3-13 A model in which three converters are connected in series

Figure 3-12 A typical configuration of a current source in PBU

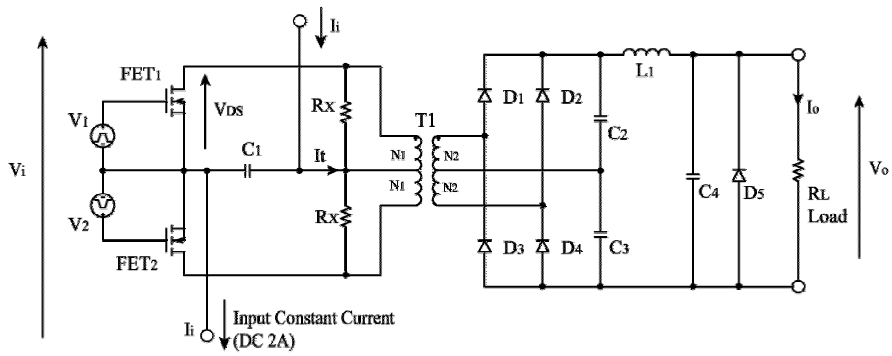


Figure 3-14 Electric circuit of the CC/CC converter used in the simulation

In order to address these issues, a prototype of the basic circuit was made and performance was evaluated. The followings are referred from K. Asakawa et al(8).

Figure 3-11 shows the measured current-voltage characteristics of the outputs of three CC/CC converters. The three converters have the proper slope resistance of about 5.6kΩ and have the similar output characteristics. This means that these three converters can be connected in series and can share the output.

Figure 3-12 shows a typical configuration of a constant current source in PBU. Their inputs and outputs are connected in series. One of three converters is a spare and its input is shunted. When one of the working converters fails, its input will be shunted and the spare converter will be activated. Assuming the three converters of **Figure 3-12** are connected in series and the output current is 2.05A, the output voltage of the three converters are between 275V and 310V. Assuming the current being 2.05A, the required output power of the PBU becomes 3.9kW. In order to realize this output power of 3.9kW, eight converters should be connected serially.

Figure 3-13 shows a simple model in which three converters are connected in series. Each converter is represented by an ideal constant current source I_i and an output resistance R_i. Output voltage V_i of each converter depends on I_i and R_i. If the difference between each I_i and R_i is larger, the difference between the output voltage of the converters also becomes larger, and each converter can not share the output power. Therefore, it is important that the I_i and R_i of all converters match with each other. As I_i and R_i depend on coupling coefficients of the transformer, loss of cores, and resistance of FETs, it is important to evaluate the relation between the output characters and the deviation of these values. The followings are the results of the computer simulations of the converter to evaluate the above relation.

3.6.3 Computer Simulation of the constant-current to constant-current converter[8]

The simulation was done using a general-purpose circuit simulation software. The model for the simulation was based on the prototype converter shown in **Figure 3-14**. The accuracy of the simulation deeply depends on the model of the transformer. The linear core model was selected for the transformer T1 as the actual magnetic flux density was far lower than that of the saturation level. In the linear model, a transformer was represented by two inductances corresponding to each winding and the coupling coefficient. The measured inductances were used for the simulation. Resistance R_xs in the primary of the transformer shown in **Figure 3-14** represent the loss in the ferrite core, transitional switching loss of the FETs and electric resistance of the winding.

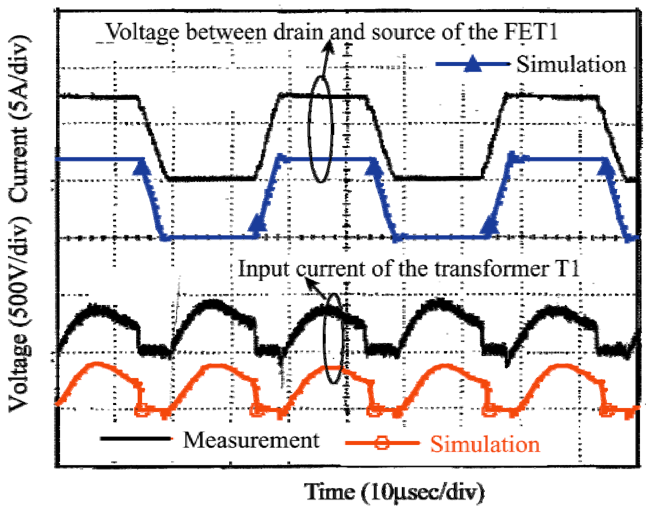


Figure 3-15 Comparison between observed waveforms and simulation results

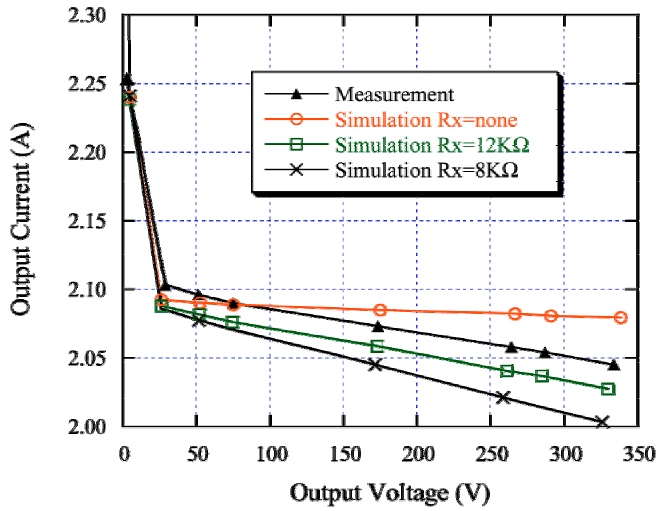


Figure 3-16 The relation between output characteristic and R_x representing the loss of the transformer and FETs.

Figure 3-15 shows the comparison between observed waveforms and simulation results. The upper two waveforms show the source-drain voltage of the FET1, and the lower two waveforms show the input current I_i to the transformer. The coupling coefficient of the transformer used in this simulation was selected so that the calculated current waveform coincided with measurements. The coupling coefficient obtained thus was 0.992, that shows good conformance with the calculated value of 0.994 using leakage inductance. That the simulated waveform well coincides with the measured waveforms shows the simulation model is reasonable.

Figure 3-16 shows the relation between output characteristic and R_x.The output characteristics with R_x of 12KΩ coincide well with the measured one. It is also clear that the deviation of resistance R_x has affect on the output characteristics.

Figure 3-17 shows the output characteristic where the on-resistance of FET(Ron) is used as a parameter. It is clear that the deviation of on-resistance of FET has little affect on the output characteristic. This is because the converter is driven with constant current. The winding resistance of the transformer also has little affect on the output characteristics for the same reason. However, these resistances have influence on the efficiency of the converter.

Figure 3-18 shows the output characteristic of the converter where the coupling coefficient of the transformer was used as a parameter. This figure shows that coupling coefficient has little influence on the output characteristic assuming it is larger than 0.99. Usually, the coefficient of coupling of 0.99 or more is reasonable.

The efficiency of the converter as a function of output voltage is shown in **Figure 3-19**. Neither the drive circuit nor the control circuit is included in the calculation of the efficiency. The simulation and the measurement show good correspondence in higher voltage region. The efficiency of 95% is obtained in higher voltage region. The detail of the loss in the higher voltage region is shown in **Table 2**. The loss of the core is estimated to be about 3W. It is clear that the switching loss of FET is dominant.

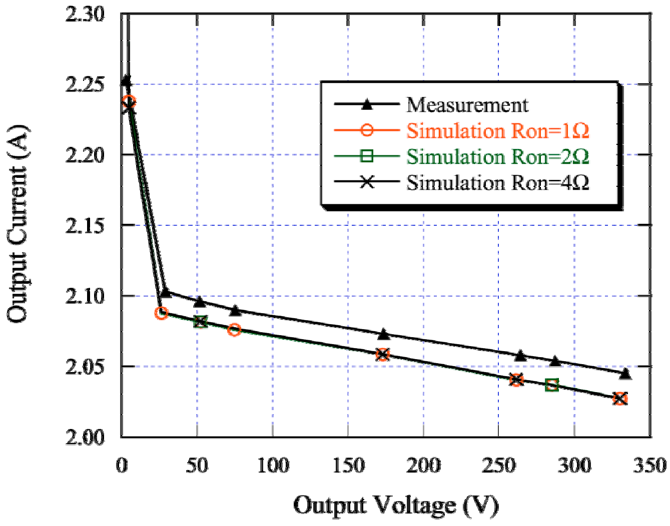


Figure 3-17 The relation between the output characteristic of the CC/CC converter and the on-resistance of FET

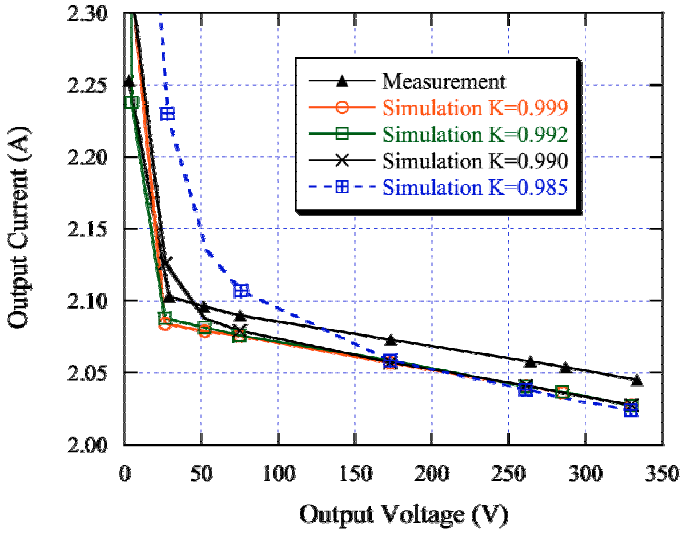


Figure 18 The relation between coupling coefficient of the transformer and the output characteristics of the CC/CC converter

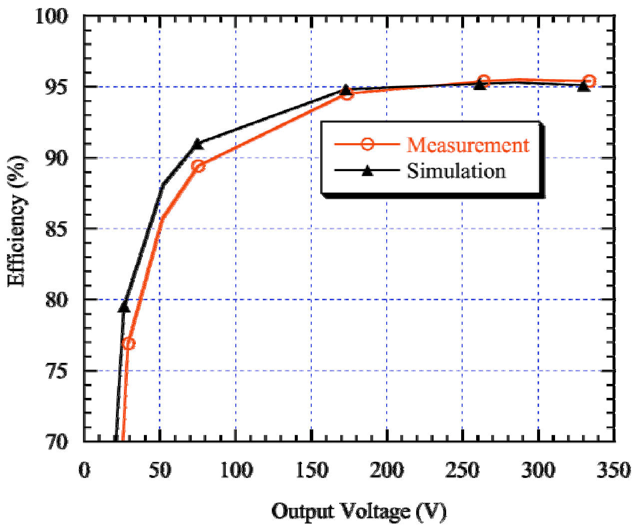


Figure 3-19 The efficiency of the CC/CC converters

3.6.4 Remaining issues

Through the experiments and computer simulations, basic possibility of CC/CC power feeding system was presented. The basic function and characteristics of the proposed CC/CC converter was excellent. However the following important issues remain for the future study.

(1) Reliability

The reliability of the system is heighten by increasing the redundancy. However more detailed study and evaluation concerning reliability will be needed

(2) Size, weight and onboard handling

As described in **Section 3.2**, handling on the cable ship is one of the important issues. It is related with the shape and weight of underwater devices. Heat dissipation and electrical isolation from sea water will also affect the shape and weight. In order to handle these issues, prototype of PBU and NBU should be designed and fabricated.

(3) Surge protection

It seems that surge protection scheme adopted for the underwater telecommunication cable systems can be used for ARENA, but careful study is needed.

(4) Start-up and shut-down procedure

In start-up and shut-down process, measures against chattering due to the rapid change of load. This measure should be examined by computer simulation and experiments using models.

(5) Stability of the whole system

Stability of the whole power feeding system having long power feeding line also should be carefully examined with computer simulation. Transmission characteristics of the power deeding line should be taken into consideration.

3.7 Comparison between the systems

In this chapter, AC power feeding was studies first, and it became clear that transmission loss with AC power feeding was large, and that AC power feeding system was unrealistic. In **Section 3.4** to **3.6**, CV power feeding system, CV/CC hybrid power feeding system and CC/CC power feeding system were proposed and examined. However, as for CV/CC hybrid power feeding system, the development cost is likely to be high due to the need to develop two types of power supplies for node, one for CV power feeding and other for CC power feeding. Therefore, in this section, CV and CC/CC power feeding system will be compared.

(1) Reliability

The advantage for the CV power feeding system is that it can easily branch electric power at PBU. For CC/CC power feeding system, relatively complicated CC source is needed in PBU. If the branching power is larger, the size and heat dissipation of the CC source also becomes larger, and it becomes difficult to keep high reliability. The handling on cable ships also becomes harder. As the reliability of the PBU for CC/CC power feeding system depends on the required power, it should carefully examined furthermore.

On the other hand, power supply in NBU for CC/CC power feeding system is easier to develop than that for CV power feeding system. A similar power supply was already developed in the VENUS project. For CV power feeding system, input voltage for NBU will be 2-3kV. Assuming the input voltage being 3kV and the allowable input voltage for a DC/DC converter being 300V, 10 DC/DC converters have to be connected in serially. This will lower the reliability of the NBU.

(2) Expandability

Expandability of the system is ensured for both systems.

(3) Measures against cable shunt fault

As explained in **Section 3.1**, CC power feeding system is robust against cable shunt fault. If CC sources are placed on both side of the cable, the system can continue power feeding even if a single shunt fault occur. The fault section can be located as the system continues operation. The same measures can be used for CC/CC power feeding system.

On the other hand, as for CV power feeding system, although a measure against shunt fault was proposed in **Section 3.4**, it is rather complicated and has not yet established. Vigorous study is needed to realize the proposed system. The other demerit for the CV power feeding system is that the re-start procedure in case of shunt fault is complicated and time consuming. When repair operation is conducting with a cable ship, speedy operation will be required.

(4) Onboard handling

Size and weight of the underwater devise have great influence on onboard handling. It seems that PBU for CC/CC power feeding system and NBU for CV power feeding system are larger. As the size and weight depend on the required power, more detailed study on the required power, the size and the weight of underwater devices is needed.

(5) Surge protection

The surge protection circuit in repeaters of the optical underwater telecommunication cable system is simple and robust, it seems to be applicable to CC/CC power feeding system for ARENA. It consists only of surge absorption devices such as arrester, varistor and capacitor. On the other hand, further study is needed in case of CV power feeding system.

(6) Electroding (EL) - superimposition of low frequency AC current on feeder current

It seems that EL can be incorporated in both systems.

(7) Efficiency and heat dissipation

As mentioned above, scale and heat dissipation of PBU for CC/CC power feeding system and NBU for CV power feeding system are cases in point. As the scale depends on the required power, more detailed study on the required power is needed.

(8) Response to load fluctuations

This issue has not been discussed yet, but there seems no significant difference between both systems.

As mentioned above, both systems have advantages and disadvantages. Concerning the scale, size, weight and reliability, PBU for CC power feeding system and NBU for CV power feeding system have issues in the future. The scale of the device and reliability depends on the required power. This issue should be examined carefully including the required power.

As for the measure against cable shunt fault and surge protection, CC power feeding system has advantages. There is no significant difference in the other items. As a result of such comprehensive examinations, the CC/CC power feeding system is thought to be most promising under the given conditions.

3.7 Summary

In this chapter, the AC power feeding system was examined first, and was shown to be extremely difficult to implement due to a very low transmission efficiency.

Next, the following DC power feeding systems were proposed and comparatively examined: (a) CV power feeding; (b) CV/CC hybrid power feeding, which combines CV power feeding and CC power feeding; and (c) CC/CC power feeding, in which a CC is branched from another CC.

The CV power feeding system offers the advantage of easy power branching. However, there have been no experience of implementing such a system in deep sea capable of producing a low DC voltage from a high voltage of the order of a few kilovolts. Assuming the input voltage being 3kV and the allowable input voltage for a DC/DC converter being 300V, 10 DC/DC converters have to be connected in serially. This will lower the reliability of the NBU, and increase the size and weight of NBU.

An effective protection measures against cable faults is also required to be devised for CV power feeding system. Thus the Power Feeding System Working Group proposed a basic protection measures against cable faults. These configurations ensure the disconnection of the faulted section from the normal section. They also enables the resumption of power feeding on a node by node basis from the one closest to the landing station, thus allowing the operation of normal sections following a shutdown of the entire system due to a cable fault. However, this procedure is rather complicated and has not yet established. Vigorous study is needed to realize the proposed system.

In the CV/CC hybrid power feeding system, trunk 1 is supplied using the CV power feeding system, while trunk 2 is supplied using the CC power feeding system. This scheme brings together the advantage of the CV power feeding system, ease of power branching, and those of the CC power feeding system, robustness to cable faults and ease of insulating electronic circuits from seawater. However, the development cost is likely to be high due to the need to develop two types of power supplies for nodes, one for CV power feeding and the other for CC power feeding.

The CC/CC power feeding system has been used for underwater telecommunication cables and conventional scientific submarine cables. As mentioned above, this system offers the advantages of robustness to cable faults and ease of insulating electronic circuits from seawater. However it was not easy to branch CC into another CC. Thus, the Power Feeding System Working Group proposed a new CC/CC converter. Its prototype was developed and basic experiments were done. Computer simulation was also conducted. These experiments and computer simulation showed a promising results. The size, weight and reliability of the CC/CC converters should be examined furthermore.

Comparing the above three DC power feeding systems, the CC/CC power feeding system is considered to be most promising.

The newly proposed schemes in the feasibility study have never been established. It is therefore necessary to conduct further studies on their operation, reliability, equipment size, heat dissipation, etc. Apart from MOSFET, the use of IGBT, GTO, etc. as switching devices needs to be considered.

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