Design of an Undersea Power System for the East China Sea Experimental Cabled Seafloor Observatory

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***Abstract*—The science community has proposed to establish large-scale long-term cabled seafloor observatories in the Chinese marginal seas. In this preparation phase, a small-scale experimental cabled seafloor observatory in East China Sea is under construction. The overall system structure of the experimental observatory is introduced. The critical power components of the undersea power system, which are the power feeding equipment, the submarine communications cable, and the undersea power converter, is designed and modeled. The backbone power delivery system is analyzed based on these models. The laboratory test proves the feasibility and reliability of the design. Finally, a power management system is designed to monitor and control the overall electric energy of the undersea power system.**

Keywords—undersea power system; East China Sea; cabled seafloor observatory; critical power components; power delivery; power management

I. Introduction

Large-scale long-term cabled seafloor observatories in the Chinese marginal seas are in the preparation phase, motivated by the science requirements from the science community. The concept design of these observatories presents in Fig. 1 (http://mlab.tongji.edu.cn/). East China Sea (ECS) is one of these marginal seas and a part of the Pacific Ocean, characterized by broad shelves and broad slopes under thick sediments. As one of the focuses in Earth's land-sea interactions, ECS is an ideal research area for many significant science themes, such as: the transport and flux of substances between Yangtze Estuary and ECS; observation, prediction, and evaluation of hypoxia zones; monitoring and prediction of natural disasters; and fisheries [1].

An experimental cabled observatory has been proposed in ECS for long-term and real-time observation of complex ocean processes. It can be generally divided into an undersea electric power system and a submarine communications system. The undersea power system is designed to provide sustained electric energy to various scientific equipments, such as heavily instrumented platforms, high definition cameras, and underwater robotic vehicles. The design of the observatory must be reliable, flexible, and compact under low accessibility, due to the particular constraints resulting from the subsea location and in order to facilitate future servicing. This paper presents the design, modeling, analysis, and test of the undersea power system for the experimental observatory.

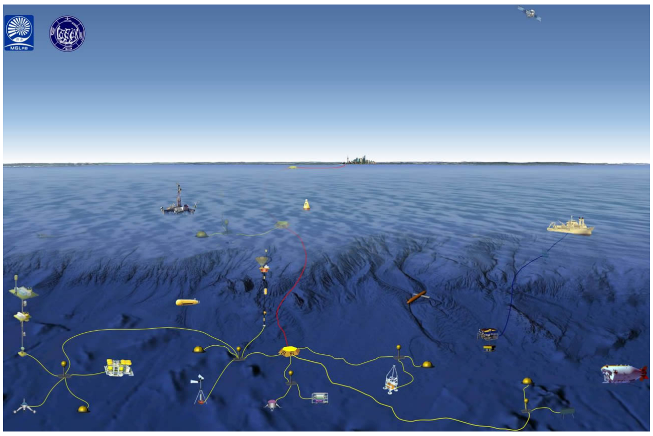

Fig. 1. The concept design of cabled seafloor obsrevatories in the Chinese marginal seas (http://mlab.tongji.edu.cn/).

II. Overall System Structure

The observatory has a shore station, a submarine cable, an undersea station, and several instrument packages. As the length of the backbone cable of the observatory is only approximately 50km at this phase, the transmission voltage is tradeoff designed to be -2kVDC. The voltage level may be raised up to around -6kVDC to -8kVDC after backbone cable extension and power component upgrade in future. The schematic diagram of the observatory shows in Fig. 2.

The shore station links the undersea power and communications system to the terrestrial power grid and communications backhaul. A power feeding equipment (PFE) in the shore station converts the utility three-phase 380VAC electric power to -2kVDC electric power, which is delivered to the undersea station via the submarine cable. An uninterruptable power system (UPS) is installed to increase the reliability of the power source.

The undersea station is designed to process -2kVDC/2kW electrical power and 2Gbps communication bandwidth. It has two high-voltage (HV) to medium-voltage (MV) DC-DC converter modules, which backup each other. They convert the -2kVDC electrical power to 375VDC electrical power and

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delivered the MV electric power to several science instrument interface modules (SIIMs) by extension cables, which is usually less than 10km.

The SIIMs are used as undersea adaptors to connect various types of sensors and instruments to the standardized payload interfaces of the undersea station. Each SIIM has several MV to low-voltage (LV) converters. They convert the 375VDC electrical power to 48/24/12VDC electrical power and feed them to multiple science loads through instrument cables, which is usually less than 100m.

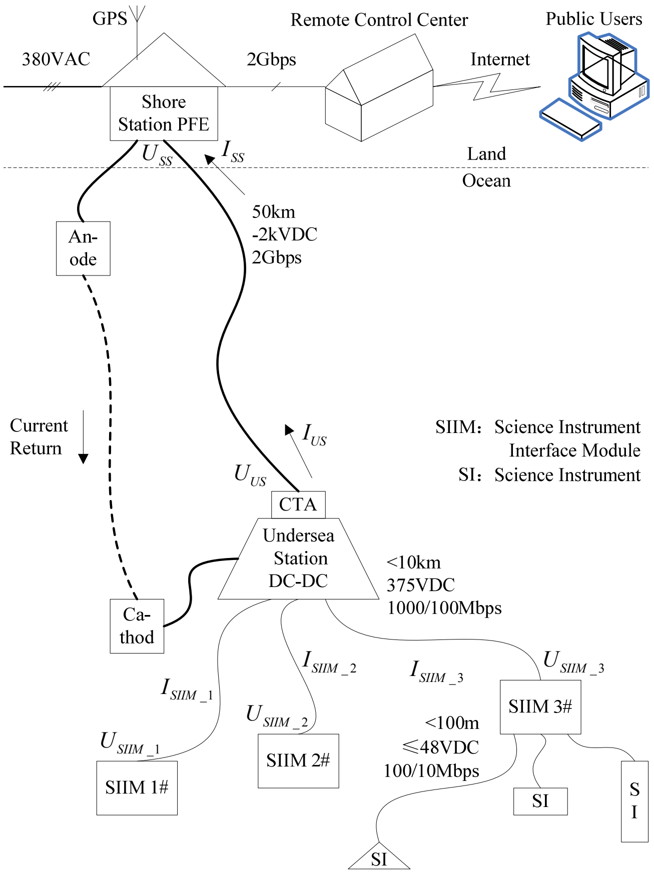

Fig. 2. The schematic diagram of the ECS expeirmental cabled seafloor observatory.

III. Critical Power Components

The observatory applies DC distributed power system (DPS) architecture, using cascaded DC-DC converters of multiple voltage levels. The critical power components of the observatory are the PFE, the submarine cable, and the undersea converters. The block diagram of the undersea DC DPS of the observatory shows in Fig. 3.

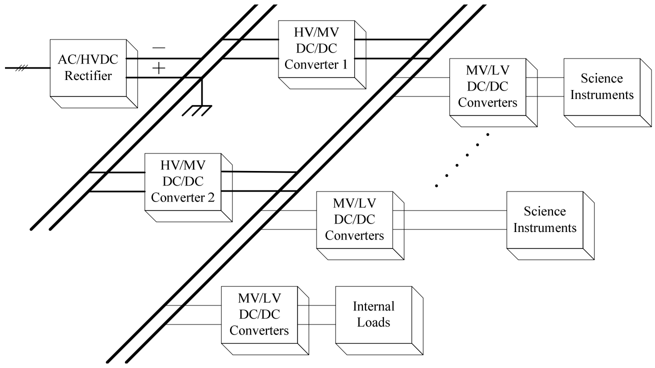

Fig. 3. The block diagram of the undersea DC DPS of the expeirmntal observatory.

A. Power Feeding Equipment

In submarine communications industry, PFEs usually use high-frequency (HF) switching converters, providing constant current output of around 1A or even lower. In the ECS experimental observatory, a phase-controlled PFE using silicon controlled rectifiers (SCRs) is adopted. The SCR PFE has constant voltage output of maximal -3kVDC/6kW. The PFE can be modeled as a constant voltage source (CVS), as its equivalent output resistant is very low. Fig. 4 is the schematic diagram of the SCR PFE. Its U-I curve and stable region draws in Fig. 5.

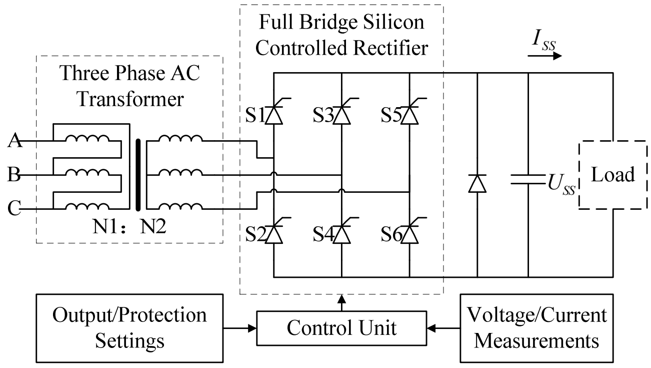

Fig. 4. The schematic diagram of the SCR PFE.

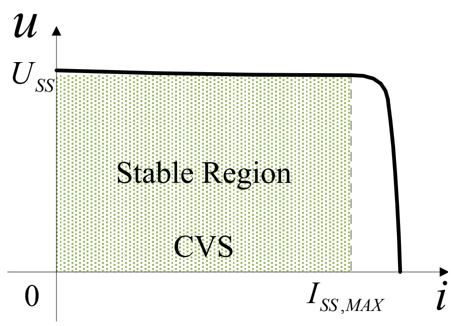

Fig. 5. The U-I curve and stable region of the SCR PFE.

B. Submarine Communications Cable

The observatory uses a standard single-conductor and double-armor submarine communications cable, in order to reduce the cable cost. The copper conductor has a resistance of about 0.96Ω/km and is used to carry the -2kVDC electrical power. The conductor and fibers are separated in the cable termination assembly (CTA) and connected to the pressure vessels of the undersea station. The backbone cable will be buried below the seafloor to mitigate the risk of outside force damages.

The long cable is a distributed parameter transmission line. For simplification, it can be modeled as a π circuit consisting of lumped components, such as resistances, inductances, and capacitances [2], which shows in Fig. 6. The capacitance and the inductance of the cable are around 0.42μF/km and 0.21mH/km respectively.

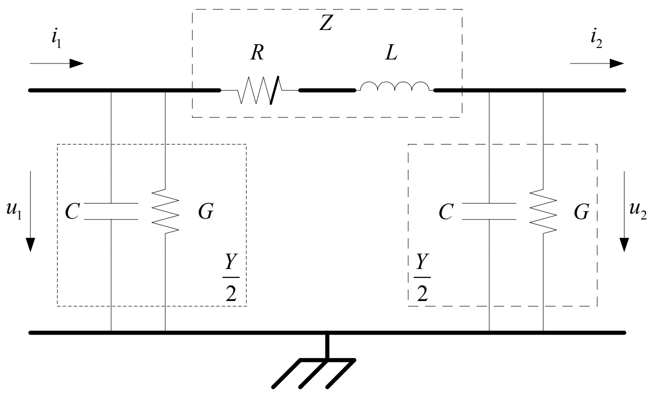

Fig. 6. The equivlent π circuit of the submarine cable.

C. Undersea Power Converter

The undersea power converter must be compact, highly reliable, and of high conversion efficiency. So HF switching convertors are more suitable than linear ones.

Generally, the HV-MV DC-DC converter has two design schemes. One is to synthesis from several power electronic building blocks (PEBBs), using LV MOSFETs as their switching devices [3]. The other has only single module to realize HVDC conversion, with HV IGBTs as the switching devices. The two design schemes have similar conversion efficiency, but the former one may have higher power density. For an input voltage level of -2kVDC or even higher, the latter one has simpler structure and thus is easier to realize high reliability at present. So the single module scheme is adopted in this phase of the observatory.

The converter is designed to operate under an input voltage range of -1200VDC to -2400VDC and a constant output voltage of 375VDC. The maximum output power of the converter is 2400kW. According to these critical input and output characteristics of the converter, the zero-voltage-switching phase-shift full-bridge (ZVS-PS-FB) topology is chosen and four 3.3kVDC IGBTs are used in one converter module. The schematic diagram of the undersea converter draws in Fig. 7. The switching frequency of this ZVS-PS-FB converter is about 20kHz and its power conversion efficiency is approximately 89% under its maximum output power.

The output voltage of switching converters is tightly regulated disregard of the input voltage change. As both of the output power and the conversion efficiency can be considered to be constant under certain payload, so is the input power of the converter, disregard of the input voltage change. So the undersea converter can be modeled as a constant power load (CPL) in the power delivery system, and thus the input resistance is negative in the small-signal sense. The U-I curve and stable region of the converter draws in Fig. 8.

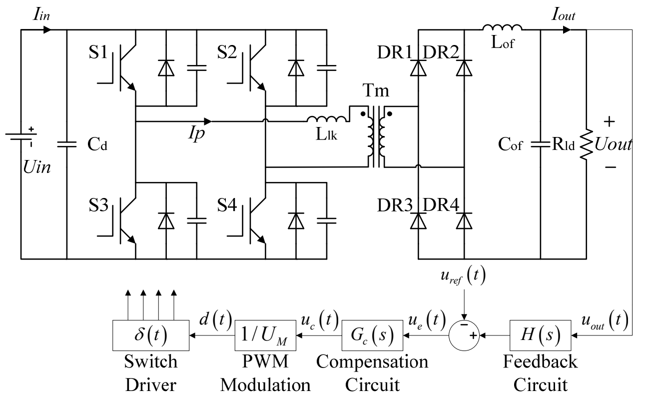

Fig. 7. The schematic diagram of the undersea converter using HV IGBTs as its switching devices.

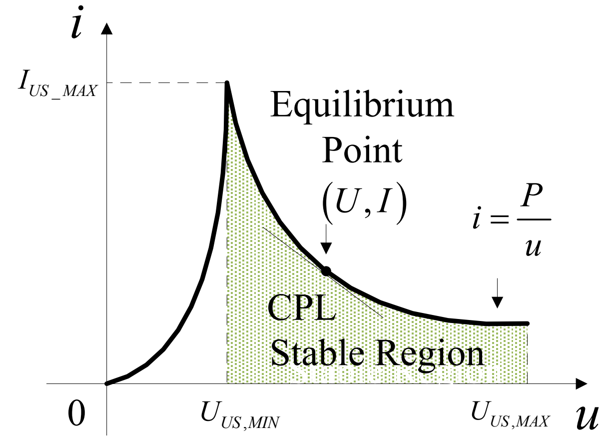

Fig. 8. The U-I curve and stable region of the undersea converter.

Due to the low accessibility and high maintenance/repair cost of the undersea equipments, the converter adopts a “1+1” redundancy design scheme, in order to increase the reliability and overall life-time. Fig. 9 is the integration design of the undersea converter consisting of redundancy modules. The structure of this converter is much simpler than the one built from many LV PEBBs, and its size is acceptable.

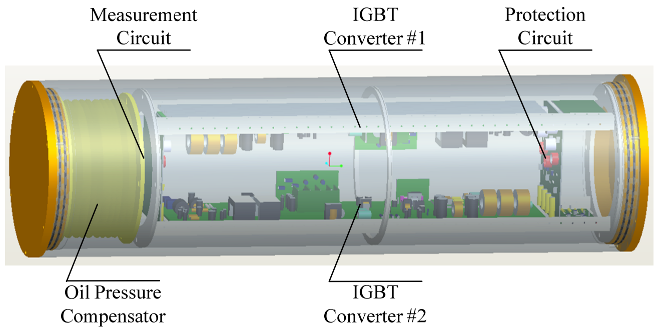

Fig. 9. The integration design of the undersea converter with redundancy modules.

IV. UNDERSEA POWER DELIVEREY

Since the submarine cable has only single conductor, the observatory backbone applies the negative DC power delivery scheme, and the seawater is used as the current returning path. In order to avoid the regular maintenance of undersea electrodes, the undersea station is installed with a platinized titanium cathode and the shore station is installed with several graphite anodes. The undersea station uses two wires (DC+ and DC-) feeding power to SIIMs, in order to avoid potential ground faults, and so do the SIIMs to instruments. The block diagram of the power delivery system shows in Fig. 10.

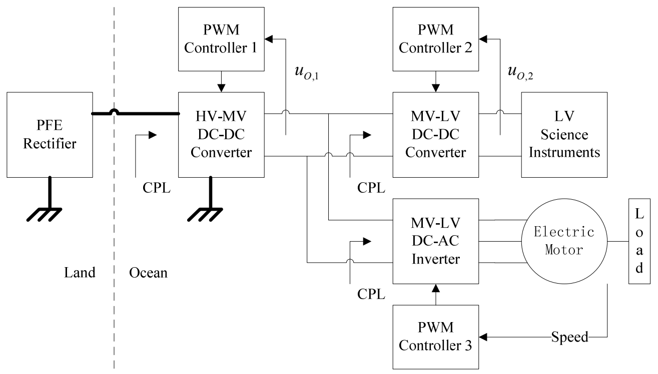

Fig. 10. The block diagram of the undersea power delivery system.

A. Power Delivery Model

The power system state can be estimated from the power delivery model, which shows in Fig. 11. In normal state, the undersea power system is operating around its equilibrium point, which is the intersection of the cable characteristic curve and the converter characteristic curve, under certain science payload (see Fig. 12).

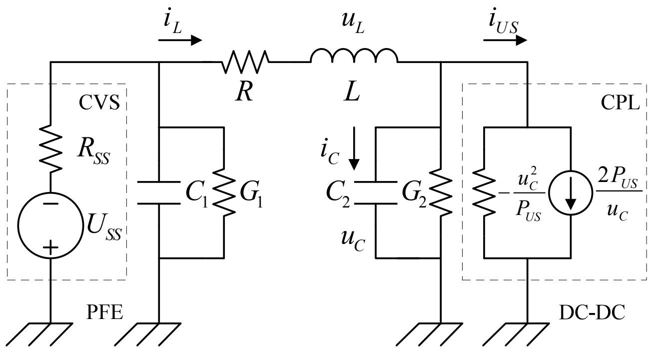

Fig. 11. The simplified model of the power delivery system of single-node cabled seafloor observaotry.

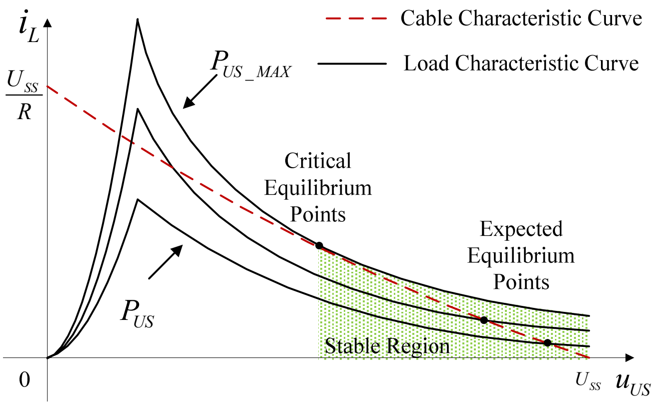

Fig. 12. The expected equilibrium points and stable region of the undersea power system.

B. Power System Experiment

The critical components of the ECS undersea power system have been tested in the laboratory. An electronic load is added to the science load, in order to simulate actual loads of different characteristics. The configuration setup of the critical power components in the laboratory test is presented in Fig. 13. The input and output voltage data of the undersea HV-MV DC-DC converter show in Fig. 14. The data of multiple temperature sensors inside the pressure vessel for the undersea converter show in Fig. 15. These sensors are installed near major heat sources confirmed by a thermal imager.

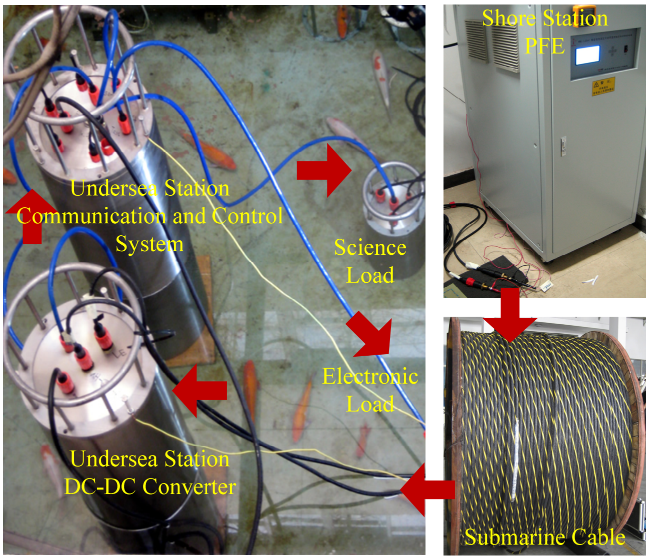

Fig. 13. The configuration setup of the critical power components in the laboratory test.

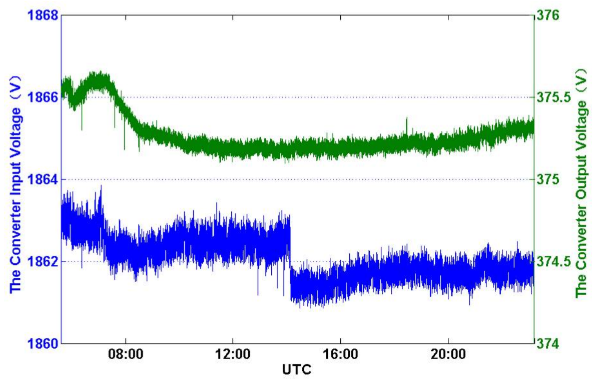

Fig. 14. The input and output voltages of the undersea HV-MV DC-DC converter.

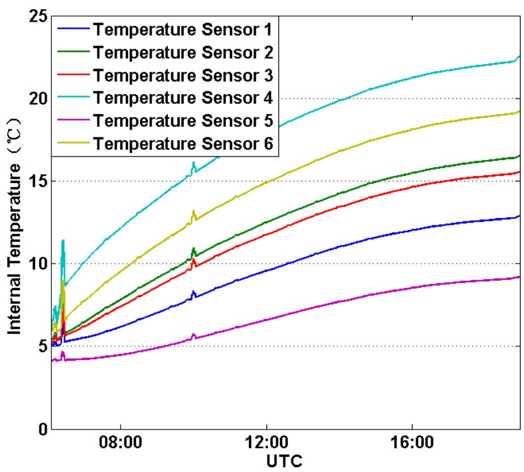

Fig. 15. The values of temprature sensors located near major heat sources inside the underea HV-MV DC-DC converter.

In the future ECS multi-node observatory, power switching branching units (PS-BUs) can be used to isolate faulted undersea stations or submarine cable segments. Power switching devices in the BU are controlled by fiber-optic signals. When a severe fault appears in an undersea station or a segmented cable, the relays in the respective BUs can act under control to isolate the fault, in order to turn the remaining system into normal operation.

V. Remote Power Management

A power management system (PMS) is developed to monitor and control the overall electric energy of the observatory, in order to increase the reliability and flexibility of the observatory operation. The PMS controllers in the shore station, the undersea station, and the SIIMs collect undersea power system state parameter data and then send them to the PMS server once per second. The PMS console sends commands to the PMS controllers through the PMS server. The communications system provides timing service to the PMS controllers, employing Network Time Protocol (NTP), in order to improve the accuracy of the results generated from the PMS. The block diagram of the PMS presents in Fig. 16.

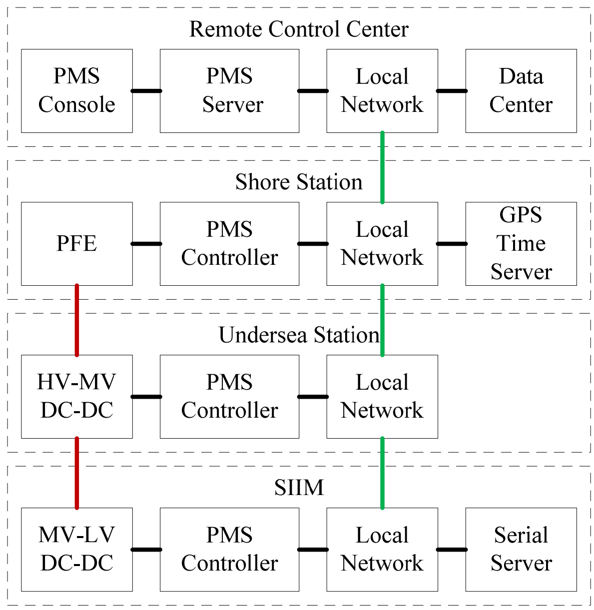

Fig. 16. The block diagram of the PMS.

Besides of a human-machine interface (HMI), the PMS mainly consists of a data acquisition module, a load management module, and a network analysis module. The relation of these three modules presents in Fig. 17. The voltage and current values and the switch status are measured to detect, diagnose, and isolate faults, as well as manage internal and external loads.

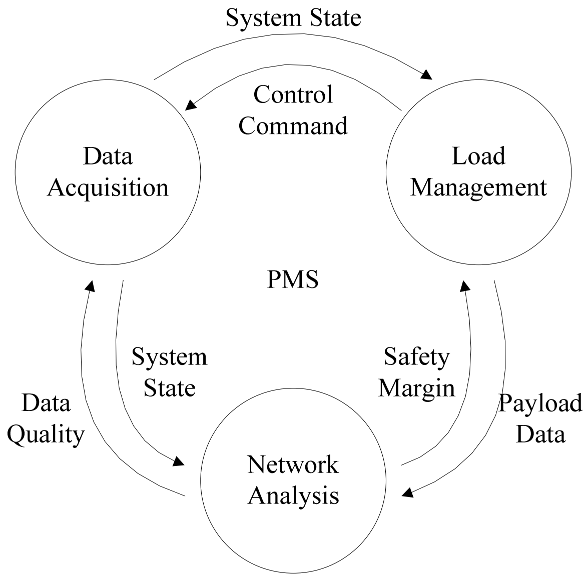

Fig. 17. The interaction of the three function modules of the PMS.

VI. CONCLUSION

An undersea power system for the experimental cabled seafloor observatory in East China Sea is introduced in this paper. The overall system structure and the critical power components are designed and modeled. The power delivery system is analyzed based on these simplified models. The laboratory test has proved the feasibility and reliability of the design. Finally, a PMS system is designed to monitor and control the overall electric energy of the undersea power system.

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