Power System for the MARS Ocean Cabled Observatory

Bruce M. Howe[1], Ting Chan[2], Mohamed El Sharkawi[2], Michael Kenney[1], Skip Kolve[1], Chen-Ching Liu[2], Shuai Lu[2], Tim McGinnis[1], Kevin Schneider[2], and Chris Siani[1]
[1]Applied Physics Laboratory and [2]Electrical Engineering, University of Washington
Seattle, Washington, 98105, USA

Harold Kirkham and Vatche Vorperian
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, 91109, USA

Phil Lancaster
Alcatel Submarine Networks
Greenwich, London, SE10 0AG, UK

Abstract – **The development of power systems is one of the most challenging technical issues in the design of ocean cabled observatories. The Monterey Accelerated Research System (MARS) will be the first ocean cabled observatory capable of delivering significant power over significant distances; it is a test bed for future regional cabled ocean observatories. At a 900 m deep seafloor node, a dc-dc converter is used to reduce the backbone voltage of 10 kV to 400 V and 48 V needed by the science users, the total maximum power being 10 kW. MARS is scheduled for installation in late 2006. The design of the MARS power system is summarized in this paper.**

Keywords: submerged power system, power electronics, underwater sensor networks, submarine cable

I. INTRODUCTION

To provide for a long-term, sustained presence in the ocean, cabled ocean obseravtories are being developed [1-10]. These will extend the power and communications infrastructure on land to the seafloor [11–20]. While low power or short cabled observatories have been long in use, there is now the need for more power farther from shore.

The planned NEPTUNE regional cabled observatory envisioned for the northeast Pacific has driven the development of a new power system that can deliver 10 kW at a seafloor node, and 100s of kW overall [21–30]. As the first necessary precursor, a single-node test bed system will be installed in late 2006 in Monterey Bay off California – the Monterey Accelerated Research System (MARS) [31]. The MARS power system is the focus of this paper. The next significant development will be the installation of NEPTUNE Canada in 2007; it will use much of the same technology [32].

After a system overview, the low voltage distribution, the medium voltage converter, the shore station, and the Power Management and Control System (PMACS) are described.

II. SYSTEM OVERVIEW

The main elements of the system are the shore station/power supply with the controlling computer, cable, and node with the medium voltage (MV) converter and the low voltage (LV) distribution system, Fig. 1. The system backbone voltage is a nominally constant 10 kV. There are sea grounds at each end of the sytem. The cable is standard telecommunications cable (Alcatel OALC4, 17 mm diameter core, 1.6 Ω/km). In the removable portion of the node structure are two pressures cases, one for the MV converter, and one for the LV system and the communications system. Scientists will be able to connect to the node for 400 V/48 V power, 100 Mb/s Ethernet, and precise timing.

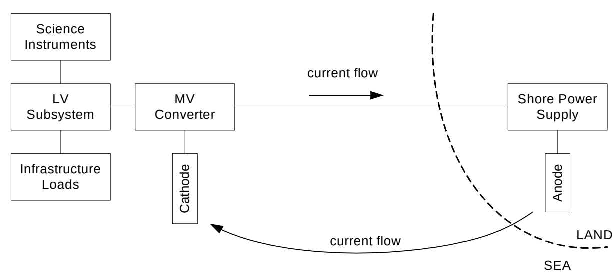

Fig. 1. Sketch of the shore to node system sketch

In the following sections we will start at the LV/science user end of the sytem and work back to shore.

III. LOW VOLTAGE SYSTEM

The Low Voltage Distribution System provides power to internal loads and external science user loads. It consists of the following major elements (Fig. 2):

- 400 V and 48 V bus voltage monitoring
- 400 V – 48 V Converter
- 48 V – 5 V/12 V Converter
- External Load Control and Monitoring
- Internal Load Control and Monitoring
- Overcurrent Protection
- Ground Fault Monitoring and Isolation

The following sections are grouped by circuit boards that implement these elements.

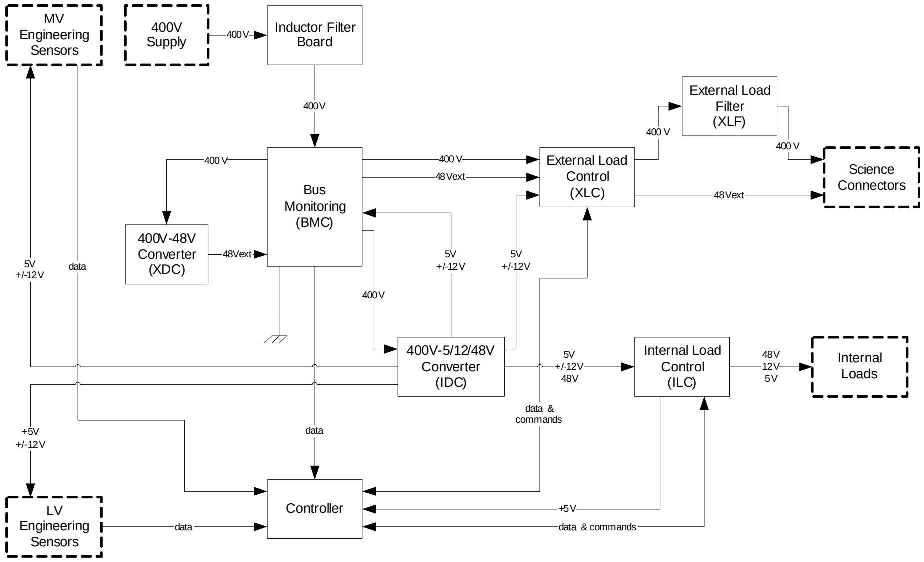

Fig. 2. LV system block diagram

A. External load control

The external load control routes 400 V and 48 V power to the eight science user connectors, providing switching and overcurrent protection. It includes the external load control (XLC) and external load filter (XLF) boards, Fig. 3. The maximum loads are 9 kW at 400 V and 1 kW at 48 V.

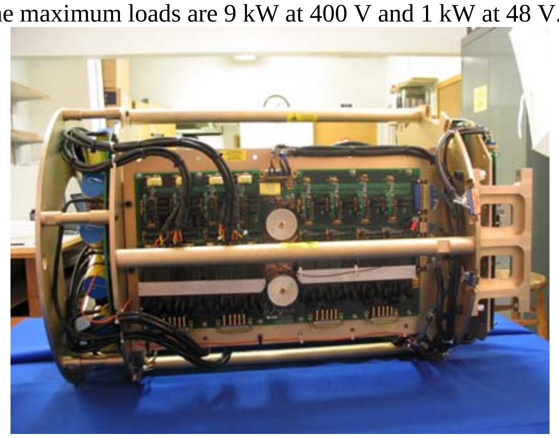

Fig. 3. The XLC (front) and XLF (left) in the chassis

The switching requirements are:

- Provide 400 V power to loads with current up to 25 A
- Protect each individual load circuit from damage due to short circuit current transients
- Protect loads on the 400 V bus from switching transients on an individual load
- Protect other loads from a voltage sag in the 400 V bus below 300 V
- Protect other loads from a surge in the 400 V bus
- Protect other loads from outage due to short circuit faults in individual loads
- Alert PMACS if a circuit breaker trips
- Provide logic for automatic reset of circuit breaker
- Provide soft-start capability to limit the in-rush current of loads

To meet these requirements a circuit with the following components was designed consisting of (Fig. 4):

- Switching FETs
- Normally closed mechanical “dead face”
- Current sensor
- Snubbing inductor in series with the load
- Comparator with hysteresis (sensor output to fixed reference)
- 7 bit counter
- Control logic
- Output filter capacitor

The basic switching circuit of the XLC board consists of a solid state FET switch that is actuated by the controller in response to a command or, in the case of an overcurrent event, locally by the node controller. In the event of a ground fault – damaged cable, leaky connector, faulted instrument, etc., – a pair of mechanical “deadface” relays will be opened on command from shore to provide a complete galvanic isolation between the internal circuitry and the fault. The mechanical switches will need to be opened after the FET switch breaks the DC current, or else the mechanical contacts will be damaged. Both types of switches are necessary because the mechanical switches cannot break the DC current without damage and the FET switches do not provide the required galvanic isolation. Due to the non-zero on-resistance the FETs will heat up when current is conducting. This heating per device can be reduced by paralleling devices. A single 100-V FET was used for the 48-V circuits and four paralleled 600-V FETs were used for the 400-V circuit.

Each of the eight external load circuits includes a solid state magnetorestrictive current sensor with an accuracy of approximately 1%.

The load control circuit breaker design has the following features (Fig. 4):

- Current from the 400 V bus is shut off when the load current exceeds 30 A with the energy stored in the inductor transferred to the load.
- The hysteresis in the comparator circuit requires that the current decrease below a set turn-on value of 20 A.
- A 7-bit counter provides for 32 reconnect attempts. Once the counter times out, a trip signal is sent to the PMACS controller. The user can reset the breaker by turning off the load control signal.

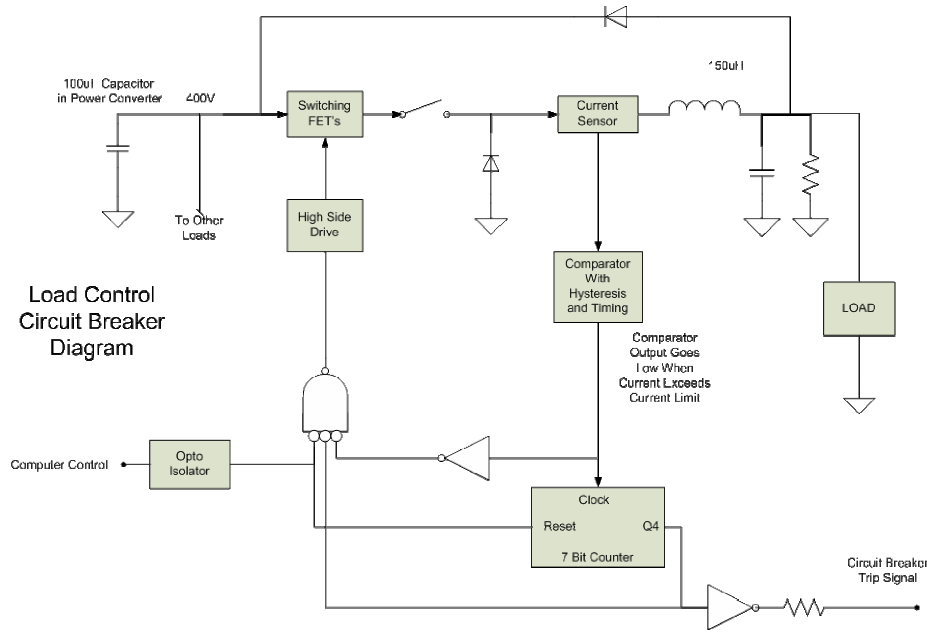

Fig. 4 – Load Control Circuit Breaker

For the operation with a high power load, the FET's are turned on and power is sent to the load; the current increases 30 A according to the dynamics of the load and the filter circuit. The comparator goes low, the FETs are turned off, the counter is incremented, and after the current decreases to about 20 A, the FETS are turned back on.

This on–off cycling action provides a soft-start mechanism to power the load and at the same time limits the load current. The action described above continues until the first 32 cycles have elapsed or the load current settles at a value below 30 A. After 32 cycles, the load is disconnected and the user is notified via the circuit breaker trip signal. The user can reset the circuit breaker by turning off the signal to the optoisolator. If the current settles to a value below 30 A before 32 cycles (a few hundred microseconds) have elapsed, the powering of the load continues.

In addition to this "fast" hardware circuit breaker, there is also a "slow" software overcurrent protection that is accomplished by the node controller. The controller samples the current sensor output at a rate of 100 Hz and compares the load current to the user furnished overcurrent setting. If this current is exceeded for 5–50 ms, the load is turned off.

B. DC–DC converter boards

There are two DC–DC converter assemblies–the external DC-DC converter (XDC) to power the external 48-V loads and the internal DC–DC converter (IDC) to power the internal 5 V, ±12 V, and 48 V loads. Each of these converters use Vicor COTS converter modules connected in parallel to provide the required power capacity and reliability.

The XDC uses four 600-W converter modules, which give a nominal capacity of 200% of the requirement. The converter is designed with N+M redundancy; N is the number of modules to meet the load requirement and M is the number of redundant modules. With this converter N=M=2. The converters on the IDC are also redundant (N=M=1).

With this configuration half of the modules can fail and the converter can continue to meet the load requirement. The design of the converter circuitry has minimized the effect of single-point failures. Because of the cost and difficulty associated with repairs to subsea hardware, we thought it prudent to reduce the vulnerability of the system to single-point failures. The only common component is the passive input inductor. Any of the modules can fail with either a shorted or open input or output and the converter will continue to operate. According to the supplier the most likely failure is a short circuit on the input of the FET in the module. They consequently recommend a fuse on the input line so that the short circuit would not collapse the input bus voltage. Because fuses have unknown reliability, we have used a circuit using three coordinated fuses with zero, one or two diodes in line to have "cold" spare fuses. There will only be one conducting fuse at a time and if it fails, the next fuse will take over. The paralleled modules are synchronized by transformer coupling between the appropriate pins.

In practice, the Vicor modules have relatively high amplitude noise on the output busses–several hundred millivolts. The redundancy mentioned above contributes to this because the noise level from the modules is inversely proportional to the load current and the multiple module redundancy / current sharing increases the noise per module and doubles the number of modules.

C. Bus monitor board

The voltage of the 48-V and 400-V external power busses is monitored by the Bus Monitoring Circuit (BMC) as a check on the basic system status of the system. The voltage sensor is a resistor voltage divider. An isolation amplifier must be used since the voltage signal will be at the potential of the external busses, which will be different from the internal busses and monitoring circuitry. In order to maintain isolation, a small DC-DC converter is required on the measurement side of the isolation amplifier (built into the isolation amplifier).

The voltages of the internal 5-V, ±12-V, and 48-V power busses also have voltage monitoring but do not require isolation amplifiers since they will be referenced to the same common potential.

The external 400-V and 48-V busses are monitored for ground faults due to insulation damage, connector leaks, etc. The ground fault monitoring circuitry alternately connects the two power conductors of each bus to case/seawater potential through a resistance and monitor any resulting current flow. Any current flow indicates the presence of a fault. The target is to be able to detect ground faults as small as 100 µA. The basic circuit is shown in Fig. 5; a fault on the 400-V line is detected when the ground fault switch on the 400-V return is closed (current path shown in pink).

It would be preferable if each science connector circuit could be monitored individually so that the faulted load could be identified and disconnected. Unfortunately, this is not practical for sensitivities less than about 10 mA. With the technique implemented, it is only possible to detect a fault on one of the busses. If a fault is detected, it will be necessary to cycle through the loads, turning the power off on each load until the faulted load is found.

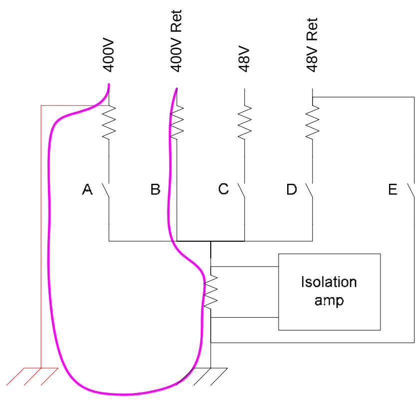

Fig 5. Bus monitor board ground fault detection circuit

D. *Internal load control board*

The Internal Load Control and Monitoring circuit (ILC) is similar to the XLC described above, with the exception that the maximum current per circuit will be lower and there is no requirement for the ground fault monitoring or deadface isolation. Each internal load (up to 16) has current monitoring and power switching. Each of these 16 circuits includes a 100-V FET switch and a solid state magneto-restrictive current sensor. The 16 circuits can be configured by solder jumpers for 5 V, ±12 V or 48 Vdc.

E. *Node Power Controller*

The Node Power Controller (NPC) is a stack of PC/104 boards that consists of one CPU board and four analog/digital I/O boards. The CPU uses a PowerPC processor with a Linux operating system. The four I/O boards each have 32 single ended or 16 channel differential analog input channels and 24 digital input or output channels.

Data from the various engineering sensors (voltage, current, temperature, pressure, humidity) are acquired at 100 Hz sample rate. Some of this high-rate data (e.g., current) is used in real time by the controller. Most though is digitally filtered and resampled at 1 Hz for transmission to the shore server where the PMACS software is running.

IV. MEDIUM VOLTAGE CONVERTER

The medium voltage (MV) converter takes the 10 kV on the sea cable and produces 400 V output. A more complete description can be found in [29,30].

The basic building block of the converter is the 200 V to 50 V, 210 W, PWM switching converter operating at 50 kHz. The series connection of all the inputs divides the input voltage among the 48 converters so that the maximum voltage at a single converter block is only about 210 V. Each stack of eight outputs generates 400 V at 1.68 kW so that six of these in parallel generate the full 10 kW at 400 V. An assembly of two converters is shown in Fig. 6.

A prototype converter has been demonstrated successfully at 8 kV in air [29]. Fig. 7. shows the ramping up of the output voltage as voltage/current is applied. Fig. 8. shows the response in output voltage as the load is increased from 0 to 5 kW; the voltage drops only 3 V over 100 µs before recovering. The output ripple (not shown) is about 200 mv pp.

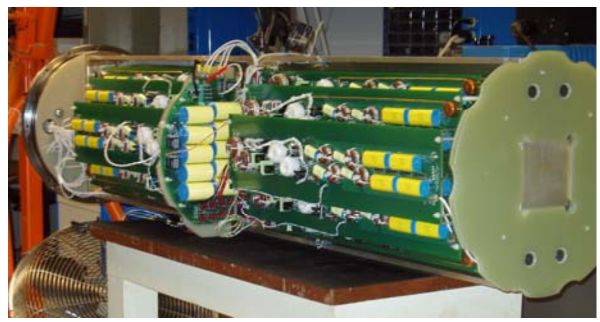

Fig. 6. Prototype MV converter assembly

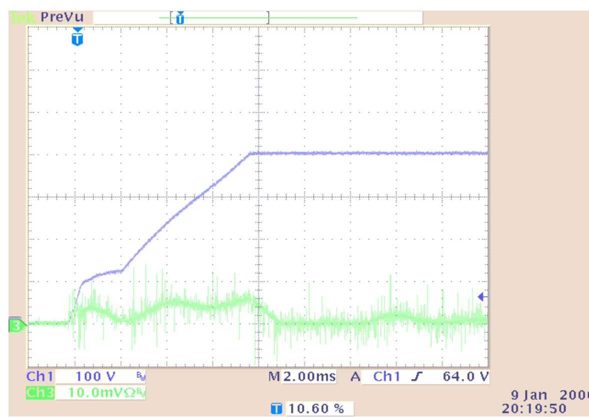

Fig. 7. Converter startup current (green, lower) and output voltage (blue, top). Input voltage –8 kV and no output load. Scale 100 V/div and 500 mA/div.

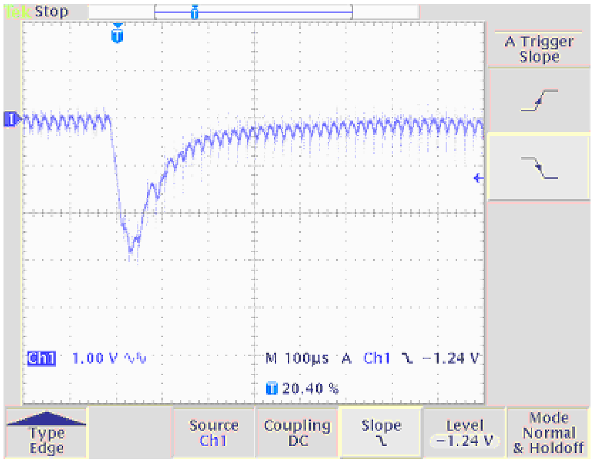

Fig. 8. Dynamic load response of the output voltage for a step load 0-to-13.2 A (5 kW). Input voltage – 8kV. Vertical scale 1 V/division, horizontal scale 100 µs/division

The results shown here are from the prototype MV converter developed at JPL. Alcatel is building the unit to be installed in the MARS node. It will be immersed in Florinert, a dielectric cooling liquid.

V. SHORE STATION

The shore station contains the shore power supply (10 kV, 1.1 A), shore ground, and the PMACS server computer. The latter is on the local area network, synchronized by GPS.

VI. POWER MANAGEMENT AND CONTROL SYSTEM

The Power Monitoring and Control System (PMACS) allows the operator to control the MARS power system. PMACS is constructed with a console/client and a server. Data gathered by the Server is sent to the Console every second. With the PMACS console, the user can perform system operation such as adjusting shore station output and managing internal or external loads. System parameters such as voltages and currents can be monitored through PMACS.

The main window shows a one-line diagram of the MARS system. The main window also has three data grids to show the shore station and science node 10 kV level voltage and current measurements, and the estimated voltage and current levels. These measurements are updated at a rate of 1 scan per second. PMACS provides a number of sub-windows that allow the operator to view detailed information and perform control functions on MARS power subsystem components. The operator can access these sub-windows with the menu bar on the PMACS main window.

The shore power supply can be monitored and controlled by PMACS with the PMACS shore power supply window.

The MARS power subsystem provides two voltage levels to external loads at 400 V and 48 V. The PMACS external load window allows the user to monitor bus voltages and currents, load currents for all 16 external loads at two voltage levels, ground fault current for 400-V and 48-V busses, and control the load status. A sample display is shown in Fig. 9.

PMACS allows the user to manipulate internal loads in four different windows, by subsystem, and by the three internal load voltages.

Other PMACS windows include the monitoring windows for all the engineering sensors, and the MV converter.

All external and internal load status changes are logged by PMACS. The PMACS events log window shows a list of operations that have taken place with time stamp and a brief description. Whenever a load switching or a change of current limit has occurred, the events log will be updated with the new operation.

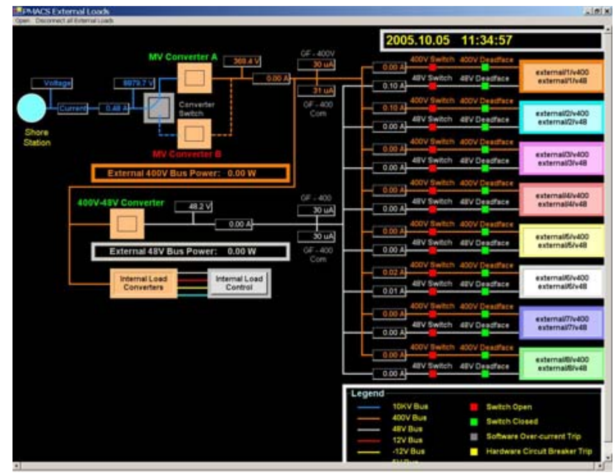

Fig. 9. PMACS External Load Window

Beside the monitoring and control functions, PMACS is also capable of performing system observation functions such as State Estimation, Topology Identification, and Fault Location. These functions follow the same methodologies developed for NEPTUNE. MARS serves as a test bed of the functions. In particular, the State Estimation algorithm uses the measurements from the shore station and the science node to estimate the system operating condition. This algorithm can reduce errors associated with the measurements.

VII. CONCLUDING REMARKS

The power system described here is in the process of being integrated into the MARS node assembly. The MARS cabled ocean observatory system is scheduled to be installed in Monterey Bay in late summer 2006. We encourage interested readers to access the project web pages [28,31] for more details.

ACKNOWLEDGMENTS

This work has been funded by the National Science Foundation Ocean Technology and Interdiscipinary Coordination program: Development of a Power System for Cabled Ocean Observatories Grant OCE 0116750 and Monterey Accelerated Research System Grant OCE 0222650.

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