Inductive Power System for Autonomous Underwater Vehicles

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***Abstract* - Underwater inductive coupling is used to recharge a lithium-ion battery pack for an underwater mooring profiler operating on a cabled deep-ocean mooring sensor network. The mooring profiler is a motor driven autonomous underwater vehicle that is attached to a vertical mooring cable suspended between the seafloor at 900m and subsurface float structure at a depth of 160m (to minimize wave dynamics and bio-fouling). A suite of on-board sensors record data as the mooring profiler travels along the cable which is transferred from the profiler to the sensor network and ultimately to shore over an inductive data link. The on-board batteries are charged inductively when the profiler enters a dock mounted below the float. Power transfer across the inductive couplers is approximately 240W with 70% efficiency.**

I. INTRODUCTION

The ALOHA-MARS Mooring (AMM) project will demonstrate the scientific potential of combining a mooring profiler vehicle with a moored deep-ocean sensor network for connection to a seafloor observatory with power and communications provided from shore via an electro-optical cable. (http://alohamooring.apl.washington.edu). This system will address the challenge of sampling the ocean with high temporal and vertical resolution over time scales that are not possible with a standard, non-rechargeable battery pack. The mooring sensor network will consist of three main components: a near-surface float at a depth of 160 m with a secondary node and suite of sensors; an instrumented motorized mooring profiler moving between the seafloor and the float; and a secondary node on the seafloor with a suite of sensors. Both secondary nodes have ROV mate-able connectors available for connecting the basic sensors and additional guest instruments. The profiler will have real-time communications with the network via an inductive data modem that will allow science data transmission and remote control functions.

Figure 1 below shows the observatory mooring sensor network that was originally planned for the ALOHA Observatory north of Oahu at the Hawaii Ocean Time series (HOT) site. For a variety of reasons, the initial year long deployment is now planned for the MARS Observatory in Monterey Bay in a water depth of 900 m.

After testing a shallow version of the mooring system in Puget Sound in summer 2007, the system will be deployed at the MARS observatory in spring 2008 and likely recovered in spring 2009. A successor self-contained battery powered mooring with an inductively charged profiler has been funded and will be deployed at the HOT site near the ALOHA Station north of Oahu in early 2009. Additional moorings of this type are expected to play a significant role in the NSF funded ORION program and the Ocean Observatories Initiative (OOI) (see www.orionprogram.org).

This project is funded by NSF Ocean Technology and Interdisciplinary Coordination, NSF OCE 0330082. The PI is Bruce Howe at APL-UW; co-PIs are Roger Lukas at the University of Hawaii, Emmanuel Boss at the University of Maine and Jason Gobat and Tim McGinnis at APL-UW.

The inductive power system (IPS) to charge the batteries on the profiler is a key new technical development of the project. The McLane Mooring Profiler (MMP) will periodically connect or “dock” to the mooring float to charge its battery pack. Due to the fact that the system is submerged in conducting seawater, the connection must not utilize any contacts that allow an electrical connection to contact the seawater. Wet-mateable connectors that have enclosed, oil-bathed contacts have some potential for this but they typically require a relatively high mating force and have a limited number of mate/de-mate cycles. The technique that has been selected is to use inductive coupling for the power. S&K Engineering has a significant amount of experience in the electric automobile industry and was contracted to make the inductive power coupler (the "dock") and the associated drive and charging electronics.

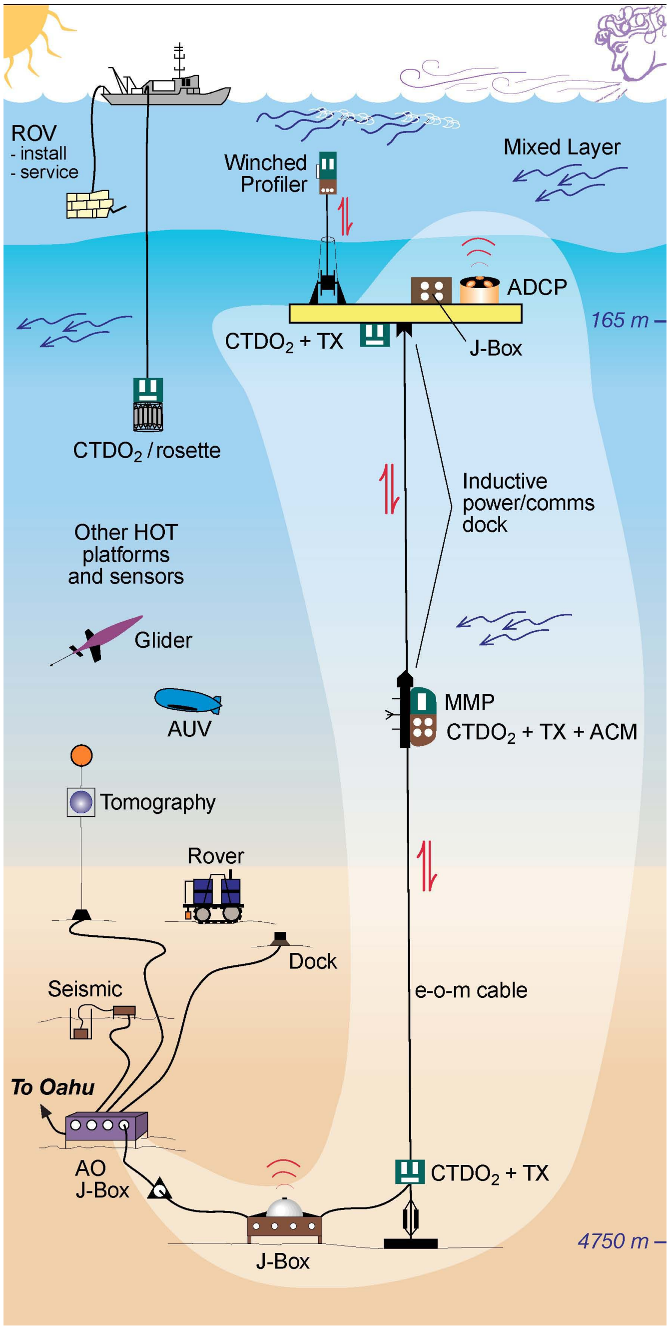

*Figure **Error! No text of specified style in document.** - Observatory Mooring Sensor Network*

II. SYSTEM DESCRIPTION

A block diagram of the charging system is shown in Figure 2. The float side has a high voltage dc-power source that can range from 150 to 400Vdc. A Boost DC-DC converter is used to create a pre-regulated voltage at 400Vdc for the second stage. The main power transfer through the inductive coupler is driven by a half-bridge inverter driving a series resonant tank circuit. The inverter operates at a constant switching frequency of 50 kHz which is above the resonant frequency. The inductive coupler has a primary side that is fixed to the mooring cable and a secondary side that is mounted on the profiler. Because of the need to operate for an extended period of time in the presence of bio-fouling, the coupler has been designed with an annular gap of 2mm. Because of the relatively large gap, the coupler has a much larger cross-sectional area than a typical power transformer. The coupler has 10 turns on the primary and 3 turns on the secondary. Because of the large gap and the separation of the windings, the coupler functions as a poorly coupled transformer and produces significantly less voltage or current in the secondary than an ideal transformer. The sea water also appears as a moderate impedance load that reduces the power conversion efficiency. The secondary side has a full-wave rectifier which may be shunted by a FET switch. The system is designed to deliver 250W at 16.4Vdc on the secondary side.

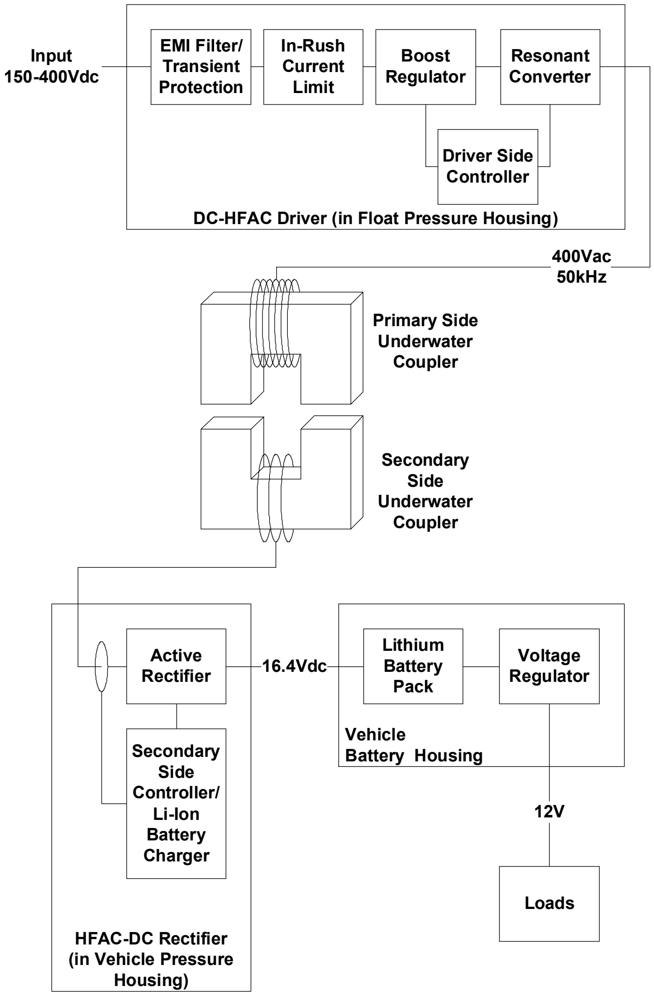

Figure 2 - System Block Diagram - Series resonant converter driving a constant frequency square wave voltage across the inductive coupler which is rectified and regulated on the secondary side.

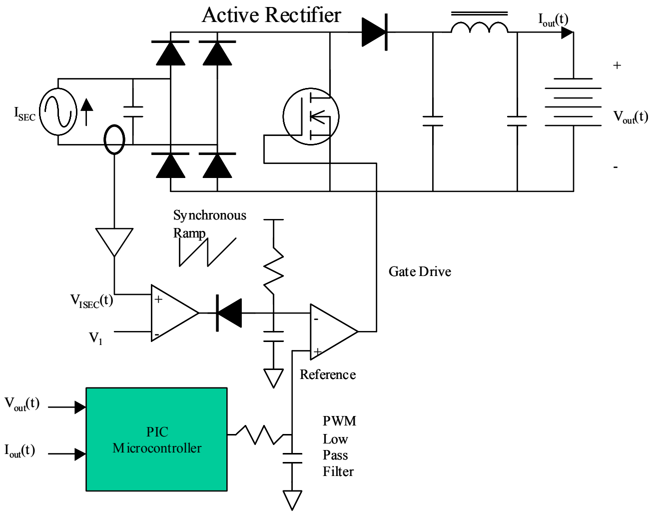

Figure 3 - A synchronous switch is used on the secondary side control the power delivery to the battery

When the battery needs charging, the MMP with the coupler secondary core will ascend and make contact with and coupler primary core. As soon as the primary and secondary cores are engaged, as indicated by a limit switch, the MMP motor will stop and the system will be ready for charging.

A. DC-HFAC Driver

The DC-HFAC Converter converts the Float 150-400 Vdc to a high frequency (50 kHz) alternating current (HFAC) that can be transmitted across the inductive coupler. It turns on once every minute and a current sensor determines whether or not any current is flowing. If the coupler secondary is present, there will be a load connected, current will start flowing and the Driver will stay on. If the coupler secondary is not present, there will not be any current flowing and the Driver will turn off after a few seconds. This technique was chosen for simplicity and does not require any other communication or feedback.

This driver circuit board, inside the float secondary node housing, generates approximately 40 W of waste heat that is conducted to the pressure case endcap through a long wedge-shaped section of copper.

B. Coupling Primary and Secondary Cores

The primary and secondary ferrite cores can survive long term submergence in seawater (cf. Sea-Bird inductive modem coupler). The shapes and mechanical design of the cores need to allow reliable coupling between the primary and secondary and be tolerant of biofouling. The primary coupler is fixed to the cable and secondary coupler is mounted to the vehicle - both co-axial to the mooring cable. A future goal is to design the couplers so that the vehicle is more easily removable from the mooring cable – particularly so the MMP could be installed and removed by ROV.

C. HFAC-DC Rectifier

The HFAC-DC Rectifier converts the HFAC power to direct current for charging the battery. The Rectifier has a micro-controller that controls the battery charging voltage-current profile appropriate for a Lithium-Ion battery. The charging starts out in constant current mode and can supply a charging current of approximately 15A. When the battery voltage reaches about 16.4V, the controller switches to a constant voltage mode.

The MMP is programmed to terminate the charge when the charging current drops below 1.5A - 10% of the initial current. Again, a copper plate attached to backside of the circuit board conducts 20 W of waste heat to the endcap.

A similar topology was developed and standardized for inductive charging of electric vehicles (EV). In the EV application, a communication loop was established between the battery side systems and the primary side by which the operating frequency was varied to control the voltage and current delivered to the battery to implement specific battery charging algorithms. In the EV application, communication initially was implemented with an RF carrier and later on an infra red (IR) carrier. Both of these technologies encounter difficulties for long term implementation in sea water. In this converter, power delivery is controlled by a FET switch on the secondary side, as shown in Figure 3. Communication between the primary and secondary sides of the system is not required. The inductive coupler when driven by the series resonant inverter looks like a high frequency constant current source. The switch is operated synchronously with the secondary current waveform. At the zero crossing of the secondary current, the switch is closed and an R-C timing circuit is reset. The current delivered by the inductive coupler is diverted from the battery when the switch is closed. The switch remains closed unit the voltage on the timing capacitor reaches a reference voltage. When the switch is open, the current delivered by the inductive coupler is used to charge the battery. A low pass filter is used to limit the ripple current at the battery.

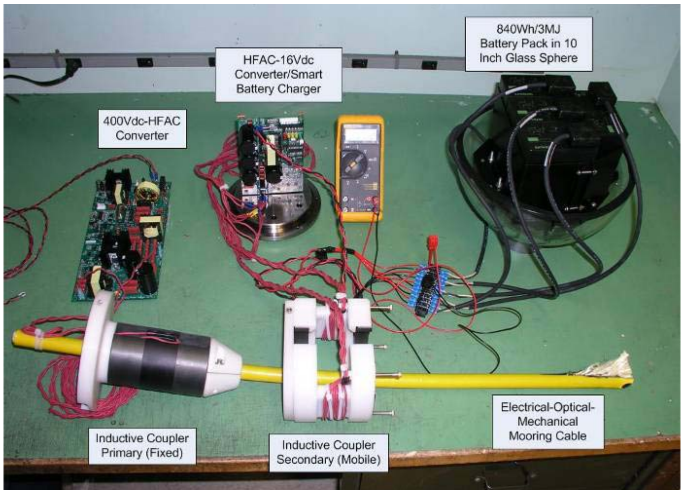

Figure 4 – Photograph of the IPS components

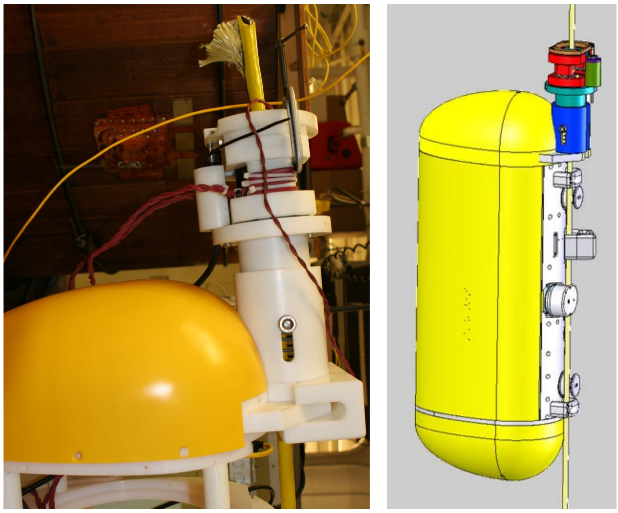

Figure 5 – Photograph and model of the secondary coupler mounted to the MMP vehicle (photo shows h the primary mounted to the mooring cable and mated with secondary)

A 16F716 microcontroller is used to implement the battery charging algorithm. The output voltage and current are sampled using an internal analog-to-digital converter. The microcontroller uses a pulse-width modulated output to produce an analog reference for the timing circuit controlling the state of the shunting switch. The pulse width is determined by the microcontroller code to implement a general purpose three step charging algorithm which is further modified for the battery selected. The charging steps are constant current, constant voltage and float voltage. The float charging is not used for this system with Li-Ion batteries.

III. EXPERIMENTAL RESULTS

A. *Lithium Battery Charging Profile*

Lithium-Ion batteries require a specific charging profile which consists of a constant current until the maximum voltage is reached and then constant voltage until the minimum current is reached. The profiler battery pack consists of a number of Li-Ion cells in series (to get the desired voltage) and in parallel (to get the required energy). The pack uses 4 sets of cells in series for a nominal output voltage of 14.4V (4 x 3.6V). The maximum charging voltage for a Li-Ion cell is 4.1V or 16.4V for 4 cells in series. When the charger is connected to a discharged battery pack, the charger will provide its maximum current capacity (in this case 15A) at the voltage of the battery pack. This constant current (CC) phase will continue until the battery pack voltage reaches the maximum charging voltage (16.4V) at which point it will enter the constant voltage (CV) phase until the charging current is approximately 10% of the initial charging current. This CC/CV profile is shown in the charging voltage-current plot in Fig 5. Because the voltage measurements were made at the battery, the voltage is slightly lower than 16.4V at the beginning of the CV stage due to I*R voltage drop in the cabling. At the end of the CV phase, the voltage is the full 16.4V due to the reduced current and resulting voltage drop.

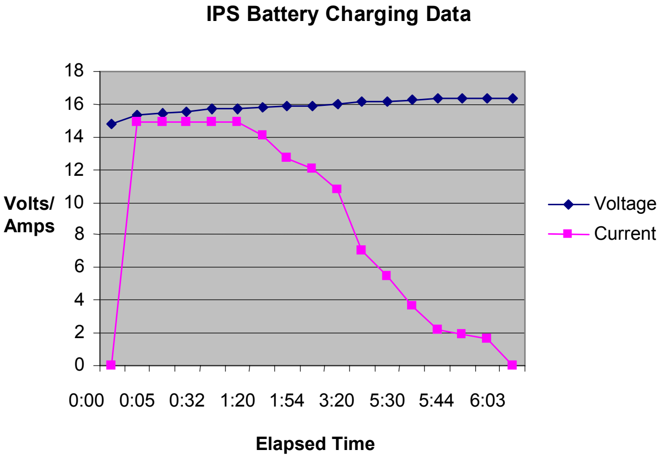

Figure 5 – Plot of the battery voltage and current during charging, measured at the battery

B. *Power Transmission Efficiency*

The efficiency of the inductive power coupler is important for several reasons. Low efficiency leads to long charge times, waste heat inside pressure cases and inefficient use of system resources. For cabled systems, the power transmission efficiency may not be critical due to the relatively high system power capacity but in the case of energy limited battery powered systems (as in the currently funded HOT Profiler project), efficiency has a direct impact on the system operations – number of profiles, profiler speed, duration, etc.

Figure 6 shows the efficiency as a function of the coupler gap and input/output voltage. The efficiencies of the deployed system is approximately 70%. It is clearly important to be sure the profiler secondary core couples efficiently with the primary core on the cable. Figure 7 shows the maximum output power as a function of the gap; with a 2 mm gap ~250 W can be transferred.

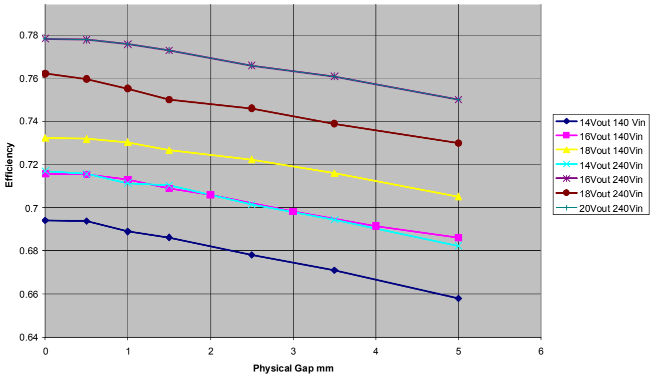

Figure 6 - Graph of Efficiency vs. Gap and Output Voltage

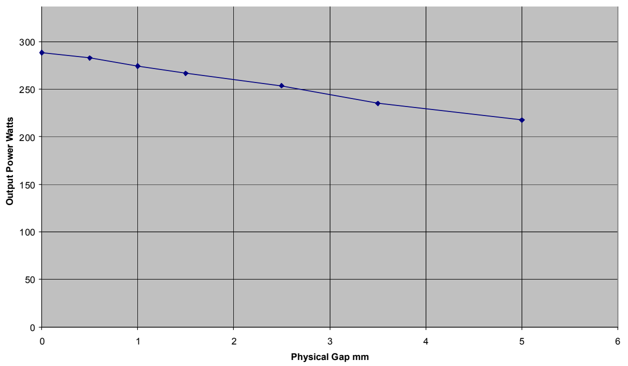

Figure 7 - Graph of Maximum Output Power vs, Gap

C. Operational Results

The ALOHA-MARS Mooring system was deployed in Puget Sound in June 2007. Through the first two months of operation, the MMP and inductive charger were generally working as expected. The profiler vehicle has sufficient battery capacity to operate for about a week and when the battery voltage gets below a remotely configurable voltage, the vehicle initiates a "charge" sequence and proceeds to the charging dock. An over-ride 'charge' command can also be sent over the inductive comms ling to initiate the charge sequence.

The IPS includes a circuit to minimize the in-rush current when the system is energized and this circuit may need some improvement because we have had some instances of voltage drop due to high current transients in the long cables.

More testing needs to be done on the circuit that determines whether the secondary is connected and either leaves the driver on or turns it off. In some cases, the driver has remained on when it should have shut off.

D. Future Enhancements

Work is currently underway on a successor self-contained battery powered mooring with an inductively charged profiler has been funded and will be deployed at the HOT site near the ALOHA Station north of Oahu in early 2009. For this system, high efficiency is important since all the energy for the system will be supplied by an underwater battery pack. Some of the design changes being contemplated for this next system are:

- lower input voltage, suitable for supply by battery pack (48V)
- higher output voltage for 6-cell Li-Ion rechargeable batteries (6 x 4.2V = 24.6V)
- higher transmission efficiency by increasing switching frequency as power output decreases (50-125kHz)
- modify secondary coupler design for installing and removing by ROV

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