Standards and Methods of Power Control for Variable Power Bidirectional Wireless Power Transfer

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***Abstract*— Unmanned and autonomous systems are used extensively for Navy missions. While most of these systems are able to operate without human interaction, limitations in power capacity place a fundamental limit on overall system autonomy. Inductive wireless power transfer provides an effective way to enhance unmanned systems (vehicles, sensors, etc.). This report examines different methods for efficiently controlling power modulation and determining which side, transmitter or receiver, commands power needs. The need for charging a wide array of systems and bidirectional power capabilities are considered, which point toward a need of underwater wireless power standards, a framework of which is proposed.**

Keywords—wireless power transfer; bidirectional; underwater; standards

I. Introduction

Battery operated systems for the maritime environment, such as unmanned underwater vehicles (UUVs) and distributed sensor networks have limited lifetimes based on the amount of energy that their batteries can hold. These systems must either be brought to the surface for battery replacement, or make watertight connections to safely recharge. In both cases, the solution requires human interaction, and in the latter, connections can corrode and fail. These requirements increase the risk to both the vehicles and users, as well as raising the total operating cost. Underwater wireless power transfer (UWPT) provides a solution to these challenges by allowing power to be inductively transferred without the risks of a direct electrical connection. By removing the need to extract the system from the water, the operational lifetime is increased and down time can be minimized.

In general, for commercial wireless power transfer applications power levels are fixed, charge rates are constant, and the cost of system components is low enough that they can be completely replaced as requirements change. Additionally, accessibility of the charging system is not really in question. For underwater systems, however, where charging capability is often required in remote locations, replacing UWPT charging components is more difficult, and deploying multiple charging nodes to meet a host of requirements is not practical. Since the power requirements of maritime platforms can range from 10's of Watts to kW's, and these requirements often change as more capability is added to a particular platform, an ideal charging system must be adaptable and able to modify charging behavior to meet evolving wireless power transfer requirements.

Another important capability for extending the functionality of autonomous underwater systems for the maritime environment is bidirectional wireless power transfer – the ability to both transmit and receive charge. This allows for dynamic allocation of energy resources to platforms that need them most, especially as mission requirements change. For example, bidirectional power transfer allows for an underwater power station to charge a UUV, and then for the UUV to transfer this power to another vehicle or remote sensor system. In this manner, a mobile "tanker" is able to ferry power between fixed systems. For the majority of consumer WPT applications, single direction power transfer is used since the device being charged will ultimately expend the energy it receives (personal electronics, electric cars, etc.). The implementation of bidirectional power transfer requires additional control protocols to ensure that the direction of power transfer is clearly established and that data on battery charging progress is correctly routed.

In this paper, the requirements for a robust bidirectional UWPT system capable of charging platforms at different power levels are examined. An operational overview of bidirectional UWPT systems is first presented, followed by a discussion of the control options that can be used to modulate the transferred power. Various feedback control schemes for initiation, control, and termination of the charge transfer process are examined, with specific focus on the nature of the data being used for control. Based on this examination, a preliminary framework for a 3-tiered UWPT standard is presented that focuses on control of relative power levels and where processing of the charging conditions (battery voltage, current, and temperature) should occur. While the proposed framework targets underwater systems, the concepts developed are relevant to any collection of electronic devices seeking to share energy via WPT.

II. Wireless Power Transfer Systems

A block diagram of an inductive WPT system with bidirectional capability is shown in Fig. 1. The system includes power transfer coils, L_{RX} and L_{RX}, along with nearly symmetrical electronics used to control the power transmitter (TX) and receiver (RX). On the TX side, the source

The work here was performed with support from the SPAWAR System Center Pacific's internal Naval Innovative Science and Engineering program.

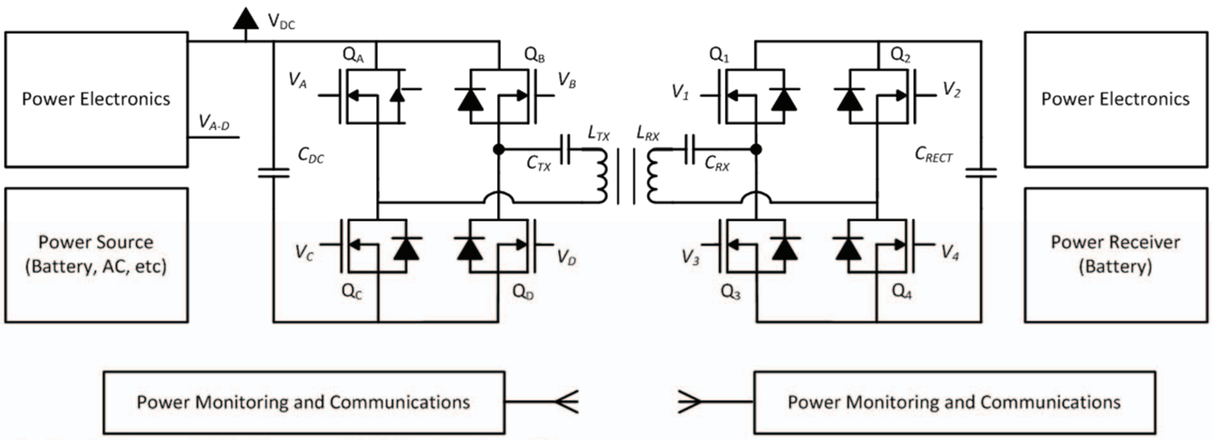

Fig. 1. Block diagram of a WPT system with bidirectional capability

provides energy to the power electronics, which generates a DC voltage, V_{DC}, and drives the gates of the full-bridge rectifier to send AC power through L_{TX}. On the RX side, power received through L_{RX} is rectified, level shifted, and delivered to the load by the corresponding power electronics. Since the goal of this work is to increase autonomy for undersea systems, the focus is on UWPT systems that utilize rechargeable batteries.

The use of the transistor full-bridge configuration on both sides allows for a single architecture that can switch between TX and RX mode electronically by controlling the timing of the gate signals. Details on the power transfer, voltage and current levels, are monitored and feedback signals are sent back to the TX using an RF communications link [1-2] or by modulating the load [3-4].

III. Methods for Control of Power Transfer

A common method to control the amount of power being transferred in a WPT system works by modulating the operating frequency of the TX signal around the LC resonant frequency formed by the coil inductance and tuning capacitor, f_{res} [1-4]. As shown in Fig. 2, the level of power transfer peaks at f_{res}, so charging should be initiated at a frequency well above or below resonance to ensure safety of the platform being charged. During charging, while the battery voltage and temperature remain below safety thresholds, the frequency of a pulse width modulated (PWM) drive signal is gradually stepped to approach the resonant frequency, thus increasing power transfer. The battery charging current is monitored during this process and slowly increases towards a predetermined set point. The set point is based on the battery size and chemistry, and may change during the course of a complete charge cycle (e.g. lithium ion). Once the current passes the set point, the operating frequency will switch directions, which leads to reduced power transfer.

An alternative method to control power transfer is achieved by varying the transmitter bridge voltage, V_{DC}. This method allows variation of the power level independent of frequency by increasing/decreasing the rail voltage as needed by the load system. Fig. 2 illustrates three power levels that can be achieved with different values of V_{DC}. While less commonly employed, this method of power control can be implemented in situations where the range of power levels required cannot be achieved with frequency modulation alone. While it is possible to set V_{DC} to a high level for all charging scenarios and vary power levels with the transmit frequency alone, the accuracy and speed of the feedback control becomes critical. For tightly coupled systems with a high quality factor, the resonant peak becomes very steep and there is an increased risk of operating at a frequency where power levels are too high for the receiving system.

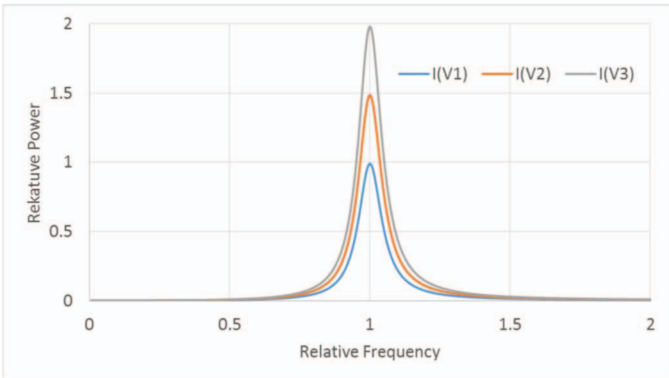

Fig. 1. Power vs. Frequency

IV. Bidirectional Power Transfer

Interoperability across maritime platforms with various power requirements necessitates a wireless power control scheme that can accommodate a wide range of power levels. This is especially critical for systems with bidirectional capabilities, where a single platform could be expected to provide power transfer from 10's of Watts (sensors) to kWs (vehicles). The frequency modulation method works safely for fine control of battery charging, and provides some flexibility in charging at different power levels, especially for underwater WPT, where all systems would operate in a narrow frequency range to minimize losses in seawater. Efficient operation typically requires the frequency of power transfer to be below 250 kHz [1].

In contrast, the voltage modulation method could allow for a greater range in power transfer and provide additional flexibility in charging systems with different power needs. For example, with a given hardware configuration and DC input voltage, the maximum amount of power that can be achieved occurs when operating at the resonant frequency. Near resonance, this limitation is directly tied to the parasitic losses in the coil. By increasing the input voltage, the power can be increased in a nearly linear manner.

A combination of these two methods, frequency and voltage control, would allow for rough tuning (voltage modulation) and fine tuning (frequency modulation) of the power transfer levels. Additionally, both methods can be implemented using microcontrollers with low-voltage, digital control. The frequency modulation can be implemented by controlling the frequency of the drive signals in the TX side inverter. Similarly, the voltage modulation can be achieved by providing the input voltage with a DC/DC switching converter, whose output can be controlled by modulating the PWM drive signal.

V. Bidirectional Power Commands

In addition to different methods to modulate power transfer levels for charging different systems, there are also two main ways the system processes charging data to determine and send commands for power transfer levels. Raw battery data (current, voltage, temperature) can be transferred from the RX to the TX, where a TX algorithm processed it and decides how to proceed [2]. Alternatively, all of the processing can be conducted by the RX system, and the only data sent to the TX are power commands, such as increase/decrease power or power set points [5]. In addition, if a common standard TX was used to charge different receivers, charge profiles could be sent by each RX to be played back by the TX.

Having battery data analysis conducted at the TX or RX each have their advantages. With the RX sending raw battery data, only the TX system needs a charging algorithm and the RX system can have less cost and complexity. With the RX sending commands or even charging profiles, there is more control to ensure that the RX system is being charged optimally, and less possibility of improper charging and risk to the RX platform. However, when bidirectional power transfer capabilities are considered, the separation between these two possibilities is less clear, as a TX can later become the RX. For bidirectional power there needs to be an initial data communication to determine which side will operate as the TX and which as the RX. In addition, both sides should possess battery data processing capability since the TX/RX role can change. Thus for bidirectional power transfer systems the following is proposed:

- all systems must have some level of basic battery data processing,
- the bidirectional RX system should always send battery charging commands or charging profiles

This commonality ensures there is never a case of two unregulated systems trying to transfer power and ensures optimal charging by allowing the RX to be in control. In addition, this allows compatibility with unregulated unidirectional RX systems that only send raw battery data, since all TX systems can process battery data. This exception lowers complexity and cost for low power systems, such as stationary sensor nodes and small systems without enough battery capacity to transfer power.

Another aspect of bidirectional power transfer critical to autonomy is the negotiation procedure that occurs before power transfer begins to determine TX and RX roles. From an underwater system level, large power stations will transmit power to vehicles, and vehicles will deploy stored power to smaller distributed sensor nodes. However, in a number of cases, this generalized model of system level power flow is insufficient. Which direction should power flow when two vehicles of comparable size meet? Could a remote power depot be resupplied by a large tanker vehicle through UWPT?

One potential solution to address conflicts caused by uncertainty in the direction of power transfer is the use of a prioritization scheme built into the programming of the autonomous assets. Each platform in a constellation of undersea assets would be provided a numerical energy priority (EP) between 1 and 10, where the lower priority system acts as the TX and the system with higher priority acts as the RX. EP1 would always acts in TX mode and EP10 always in receive mode. For example, in the case of the power depot, an EP2 might be appropriate; the depot would always act in TX mode, unless an energy tanker, set to EP1 was sent to the depot to refuel. For vehicles, this prioritization scheme would allow for those with a critical mission to be set with the highest priority value. Any encounters with other vehicles would result with the lower energy priority systems sacrificing some of their stored energy to ensure that the high priority mission is achieved.

VI. Framework of UWPT Standards

The concepts and benefits of power modulation by voltage or frequency modulation, and their control being informed by battery analysis by the TX or RX have been explored with a focus on bidirectional power transfer. Prioritization of energy transfer has also been discussed. These considerations make it apparent that in order to have interoperability across an array of different systems, especially for the maritime environment, standardization must be developed to direct future systems. In order to have interoperability, data transfer, and bidirectional power, published standards must exist to ensure proper communication, charging at different power levels, and dimensional hardware compatibility.

A three tier standard is proposed for different power level systems, overviewed in TABLE 1:

(1) Low Power for systems that require less than 50W charging with no bidirectional power required (a low power system would not have capacity to charge other systems) and only needs to send raw battery data. This tier allows for low cost and complexity systems and eliminates the need for a TX charging algorithm.

(2) Medium Power for UUVs and larger systems that require less than 250W charging with bidirectional power and a TX charging algorithm for battery analysis capabilities. The bidirectional requirement may be excessive in some cases, but ensures that all Medium Power systems can transfer power if needed.

(3) High Power for large UUVs and underwater power stations that can transmit up to 10kW, have bidirectional power, and a TX charging algorithm for battery analysis capabilities.

This proposed standard is based on current and future systems and interest within the Navy and DoD. The Medium and High Power systems will require common communication protocols so they can handshake to determine power direction, communicate charging commands, determine power transfer prioritization, and charge Low Power systems. Each standard will also need hardware guidelines to ensure coupling between coils and overall compatibility.

TABLE 1: BIDIRECTIONAL WPT STANDARDS

Standard Power Level	WPT Power (W)	Bidirectional Power	Tx Charging Algorithm	RX Send Power Commands
Low (LP)	50	N	N	N
Medium (MP)	250	Y	Y	Y
High (HP)	10k	Y	Y	Y

Examining what will work for Navy needs in relation to commercial industry standards will help narrow the focus area. The Qi communications scheme is mainly unidirectional (RX to TX) which works for cost and spaced constrained assets, but could hinder power control at larger power levels [4]. Using a separate wireless standard like WiFi, ZigBee, or Bluetooth for control communications similar to how A4WP uses Bluetooth will improve interoperability and function independently of TX power levels [5]. The practicality of using a higher resonance frequency for data on the same WPT coil hardware should be examined as well [6].

Providing coil and coil housing standards will prove to be a challenge due to the variety of UUVs that can benefit from WPT and vendor willingness to modify designs to accommodate a proposed standard. Navy WPT testing standards also need to be developed to aid in comparing different systems to the same metrics and to check systems against Navy WPT standards.

VII. CONCLUSION

This work presented a preliminary framework for standardization of UWPT eco-system that provides interoperability between nodes of different power levels. Bidirectional power transfer capabilities were presented, both architecturally and operationally, and a power transfer prioritization scheme has also been proposed. Future work will focus on the demonstration of proposed standard and modifying the initial framework to meet new operational requirements.

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