Development of a Multi-source Energy-Harvesting Buoy for Underwater Acoustic Sensor Networking Application

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ABSTRACT

We present our ongoing work on developing a multi-source energy harvesting buoy that could be used to power underwater acoustic sensor nodes deployed on the surface of a sea or an ocean. The buoy harvests energy from three different sources; wind, solar and wave energy. The collected energies are combined optimally through a power management circuit, which can deliver the harvested energy either to a gateway sensor node or replenish its rechargeable battery for future use. A prototype of the multi-source energy harvester is presented with some preliminary results.

Keywords

Multi-source energy harvesting; ocean energy harvesting; power management; wind, solar and wave energy harvesting.

1. INTRODUCTION

Unlike terrestrial RF wireless sensors, underwater acoustic (UW-A) modems require significantly more power to operate [1, 2]. An important factor to take into consideration is the large transmit power of the UW-A modems, which is in the range of 1.78 W - 20 W [3], compared to 88.2 mW [4] in terrestrial RF sensor networks. In addition, the energy of an UW-A modem's battery is limited and replacing or recharging the battery is not practical [1]. As a result, it is essential to have an energy harvesting mechanism that can constantly supply power to the underwater sensors.

Existing ocean energy harvesting buoys collect energy from one or two sources, such as solar, wind or waves [5, 6]. Instead, we propose a multi-source ocean energy harvesting mechanism that can potentially harvest energy from three different sources: wind, solar and waves. The architecture of the buoy will encompass all three harvesting mechanisms on a single framework and will provide optimum aggregate power efficiently. We will model and analyze the aggregate power harvested from the three different sources.

The architecture of the multi-source ocean energy harvester is shown in Fig. 1. Wind, solar, and wave energies are harvested through a windmill, an array of solar cells and a set of linear electromagnetic generators, respectively. Wind and wave energy harvesters generate alternate current (AC) voltage, which is converted to direct current (DC) using an AC/DC converter circuit. The maximum-power-point tracking (MPPT) circuit regulates the harvested power by maximizing power extraction under different conditions. The generated power from each sources is delivered to an energy harvesting power management integrated circuit (PMIC). The PMIC in turn regulates the voltage generated by the three different sources, as each individual harvester provides a different amount of voltage. The aggregate harvested energy is stored in a rechargeable battery, which could be connected to an acoustic sensor devices, such as acoustic modems or a gateway device using both acoustic and radio frequency (RF) communication. All three harvesting mechanisms, including the power management unit are designed efficiently to reside inside the harvesting buoy. The designed buoy would be very useful for the underwater acoustic server node deployed on the surface of an ocean or a sea that constantly collects data from the deployed nodes and transmits it through an RF link to a satellite or an off-shore station.

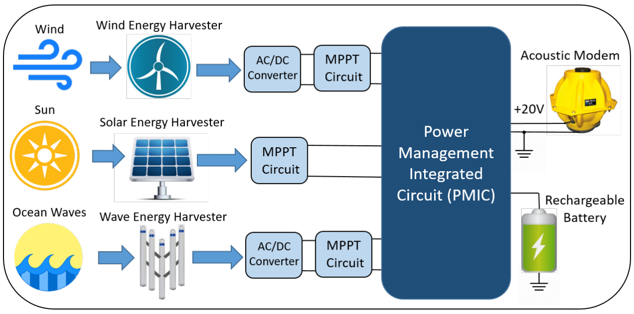

Figure 1: Multi-source ocean energy harvester architecture.

2. PROTOTYPE OF MULTI-SOURCE ENERGY HARVESTING BUOY

The idea behind harvesting energy using multiple sources is to provide continuous supply of energy to an underwater communication system throughout the day. For example, during a sunny day when the water is fairly calm and there is not much wind or waves the solar cells can harvest energy. Similarly, during the night the system can harvest energy from wind and/or water waves.

A prototype of the proposed multi-source ocean energy harvesting buoy is shown in Fig. 2. The dimensions of the designed prototype buoy are 0.7 m $\times$ 2 m (width and height). There are

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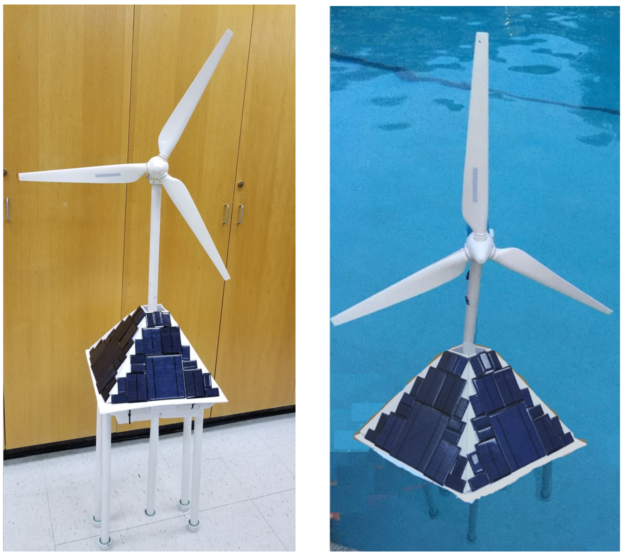

(a) (b)

Figure 2: Multi-source ocean energy harvesting buoy (a) in the lab, (b) deployed in a swimming pool.

three different sections that harvest the energies. First, the top portion is a windmill that converts wind energy into electrical energy. The middle portion is an array of solar cells on a pyramid shaped sturdy plastic structure designed to optimize the solar energy absorption. All the electronics and the rechargeable batteries reside in a waterproof case inside the pyramidal enclosure. Buoyancy of the harvester is preserved by a styrofoam structure underneath the pyramidal base. Finally, the bottom portion is comprised of five columns of linear electromagnetic generators (LEGs) that harvest energy from waves.

2.1 Solar Energy

Depending the configuration of the size and design of the harvester the array of solar cells can be designed accordingly. In our prototype, on each side of the pyramidal structure, we have used one 5 V, 2.5 W; 4 of 5 V, 0.8 W and 12 of 5 V, 0.3 W solar cells, respectively. On each side of the pyramid the solar array has a total capacity of 5 V, 9.3 W of power rating. This arrangement can be used to power either a 5 V battery at 37.2 W or a 20 V battery at 9.3 W. At an operating efficiency of 45%, the output power would instead be 4.2 W at 20 V or 16.7 W at 5 V.

2.2 Wind Energy

The wind energy depends on the wind speed and the windmill design. The average windmill power can be expressed as,

$$P_{wind} = \frac{1}{2}\rho A v^3, \tag{1}$$

where ρ is air density, v is wind speed and $A = \pi r^2$ is windmill sweep area of radius r. Experiments were conducted in a laboratory using a light weight windmill of radius $r = 40$ cm rotating at 100 and 107 rpm speeds the pick-to-pick voltages of 3.64 V and 3.96 V; currents 1.22 A and 1.28 A, respectively was observed.

2.3 Wave Energy

LEGs are made of five columns of plastic tubes waterproofed on each side in which a long column of coil wound on a thinner plastic pipe is inserted. Inside the plastic tubing of the coil a series of 11 strong vertical cylindrical magnets of length 4 cm each are

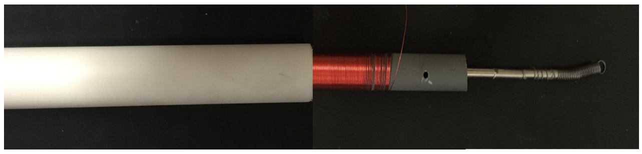

Figure 3: Inside view of the linear electromagnetic generator.

inserted and suspended from each end by a spring system to allow it to oscillate freely in vertical direction. Due to the wave motion, the 5 columns along with the magnets inside will oscillate vertically through the column of coils and thus generate electrical energy. The length of each pipe is 65 cm. In Fig. 3, part of the coil, magnetic amateur and spring is depicted. The power generated depends on the speed of oscillations and the design structure of the LEGs.

The average power generated by the LEG system can be expressed as

$$P_{wave} = \frac{E^2}{4R}, \tag{2}$$

where R is the load resistance and $E = N\frac{d\phi}{dt}$ is the electromotive force in which N is the number of coil turns and $\phi(t)$ is the flux linked with coil, which can be expressed by

$$\phi(t) = \hat{\Phi}\,\mathsf{sin}(\frac{2\pi}{\lambda}y(t)), \tag{3}$$

where $\hat{\Phi}$ is the peak flux produced by the permanent magnet, λ is the magnetic wavelength in meters and $y(t)$ is the vertical movement of magnet generated due to the water waves, which can be expressed as

$$y(t) = \frac{d}{2}\mathsf{sin}(\omega_m t), \tag{4}$$

where d is the maximum generator travel distance and ω_m is the water wave frequency in rad/sec.

2.4 Aggregate Power

We will model and analyze the aggregate power harvested from the three different sources, which can be expressed as

$$P_{total} = P_{solar} + P_{wind} + P_{wave}, \tag{5}$$

where P_{solar}, P_{wind} and P_{wave} are the power generated by the solar panels, wind turbine, and five oscillating LEGs, respectively. From our preliminary analysis, the solar system provides higher portion of power compared to the wind and wave harvester.

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