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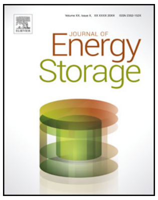

Integration of buoyancy-based energy storage with utility scale wind energy generation

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ABSTRACT

This paper presents concepts and considerations for integrating a Buoyancy Energy Storage System with a utility scale wind turbine and the Ontario, Canada energy market is used as a case study. Using derived characteristic equations of operation, a Buoyancy energy system is sized for storage of 1 MWh of electrical energy. Practical considerations of float and equipment selection are discussed and hydrodynamic drag losses calculated for the desired float velocity range. Round-trip efficiency is estimated based on calculated losses. Power generation data from a 2.3 MW wind turbine is presented along with the historic energy purchase price data for Ontario in 2015. Total revenue and net revenue resulting from storage is calculated based on historic data and a developed bi-diurnal storage program. Open water testing of a small scale system was conducted in Lake Huron which confirmed steady state operation of the system under sufficient loading

1. Introduction

Buoyancy Battery Energy Storage (BBES) is a new form of energy storage under development for the improved integration of intermittent energy sources such as wind and solar into existing electricity grids. BBES utilizes an objects buoyant property to store energy through a force transfer mechanism which couples linear underwater float motion into rotational motion as depicted in Fig. 1 [1].

When applied in an open body of water, the system features subsurface components including the float, numerous transfer pulleys, and the connection cable. The reel generator and associated electronics and controls are surface mounted and interconnected to an intermittent power source and electricity grid. This approach to storing bulk energy has several potential advantages which make the technique attractive for further research and development.

One challenge currently facing the economic-feasibility of competing large scale offshore energy storage systems such as underwater compressed air energy storage is the deployment costs associated with the transport and installation of equipment. The costs of construction offshore are several times greater than typical terrestrial construction [2]. This is further complicated when subsurface construction is required and construction diving or ROVs (Robotic Operated Vehicles) are utilized. Due to the layout of system components, BBES has the potential for full surface deployment – the pulley anchorage can be launched and sunk to depth from a barge. Float can be pre-filled with air and towed to their final location. This technique of surface installation has been used for previous experimental BBES systems [1,3]. This surface deployability is an important advantage for BBES.

The system components for BBES are existing equipment in heavy machinery and offshore industries which greatly simplifies the design and development process. By adopting from best practices from offshore oil, and subsurface telecommunication cable installation industries, the development of the system from lab to full application, can be accelerated. Furthermore, due to energy storage depending primarily on volumes of air and water, there are no thermodynamic complications or losses.

Previous experimental analysis [3] has displayed that BBES discharge force is constant with respect to both float depth and time. This confirms that BBES is non-dissipative, meaning that the medium for storage, buoyant potential energy, does not degrade over time and thus the lifespan and cycling fatigue will depend solely on the basic mechanical and electrical components which make up the BBES system assembly. Pulleys, crane reels, electric motors, and electric generators have all been in extensive use for more than 200 years and thus their design and operation is well understood [4]. Many examples exist of electric motors and these mechanical devices still in operation after more than 100 years of

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Nomenclature

BBES	Buoyancy based energy storage
Cd	Drag coefficient
EPP	Energy purchase price
HOEP	Hourly Ontario energy price
IESO	Independent energy service operator
M	Float mass
N	Number of floats in array
P	Generator power
PO	Price opportunity
R	Revenue
RR	Revenue rate
RS	Net storage revenue
ROV	Robotic autonomous vehicle
U	Float velocity
V	Float volume
η	Efficiency

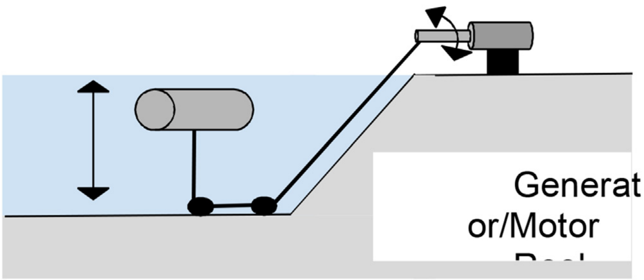

Fig. 1. BBES system for open water body.

operation and thus the potential for BBES to have 50+ year lifespan is highly possible.

One of the most attractive aspects of BBES is scalability. Unlike chemical based batteries, the primary BBES elements required for increased storage capacity are air and water, which are some of the most abundant elements on the planet. Additional materials which are typical in industrial construction such as stainless steel and plastics will also be required for the structure of the float but this is not problematic or limiting as these material resources and ubiquitous in industry. This allows for the possibility of utility scale bulk storage on the magnitude of Gigawatt-hours. Presently, energy storage techniques theoretically capable and potentially practical for approaching this level of capacity are limited to pumped hydro, and compressed air energy storage (CAES) [5]. It is the intention of the authors to demonstrate that the much less discussed BBES is also capable of this level of energy storage capacity.

2. BBES process and operation

The operational process for BBES involves the conversion between electrical, kinetic and potential energy forms through the aforementioned mechanism and machinery. The process begins with the power source, which would typically be an intermittent, renewable energy generator such as a wind turbine or solar panel array. Currently these systems supply the electricity grid with energy on an "as generated basis". Fig. 2 below displays power output data from an operational 2.3 MW wind turbine in the Port Alma wind farm located in Tilbury, Ontario, Canada. The typical intermittency is evident in the figure, with power output at a maximum during the early morning hours. The BBES system could also be connected directly to the electricity grid, with the grid acting as the power source.

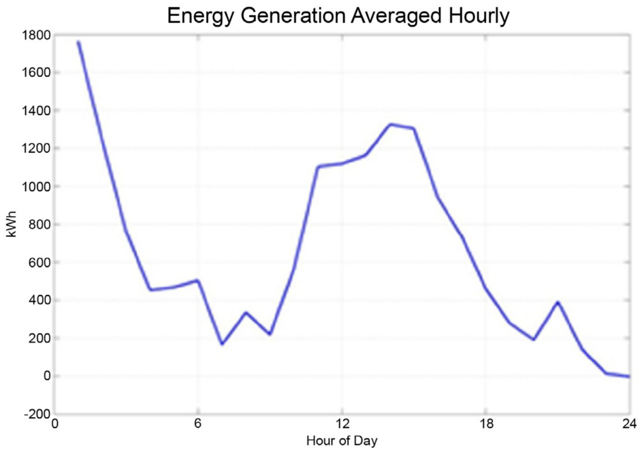

Fig. 2. Power output vs. Time for 2.3 MW wind turbine in Port Alma wind farm for date of Sept 20, 2015.

The generators are financially compensated based on the Energy Purchase Price (EPP) established by the local Electricity System Operator (ESO). The EPP is a price for supply of each kWh of electricity, which will fluctuate continuously in relation to the supply/demand balance experienced by the electrical grid as a whole. When expressed as a rate, the revenue generated by the wind turbine can be expressed in Eqs. (1) and (2) below.

$$R = E \times EPP \tag{1}$$

$$RR = P \times EPP \tag{2}$$

Where R = Revenue, RR = Revenue Rate ($/h), E = Energy generated (kWh), EPP = Energy Purchase Price ($/MWh), and P = Generator Instantaneous Power (MW). By combining energy storage to a renewable generator there are new possibilities for increased revenue generation by controlling and optimizing the revenue rate based on the fluctuating energy purchase price. Generated energy can be diverted to the storage systems at times of low demand (EPP1), storage for a period of time, and discharged at the time of high demand (EPP2). The time interval on the EPP market is 5 min. The price opportunity is defined as change in EPP between time of storage and time of discharge

$$\mathrm{PO} = EPP_2 - EPP_1 \tag{3}$$

Where PO = price opportunity, EPP_1 = current energy purchase price, EPP_2 = energy purchase price at the time of discharge. The extent of price opportunity will depend on local grid supply/demand conditions but can vary drastically in a daily time period. To demonstrate the drastic variation in EPP and show the potential price opportunity, sample data from the Ontario, Canada electricity grid was obtained from the Independent Electrical System Operator (IESO) [6]. Fig. 3A displays the daily maximum PO values for 2015. Fig. 3B displays the Hourly ontario energy price data for selected months.

As can be seen from the plots above, there are certain instances where the OHEP is a negative value. These negative prices occur when there is an excess of energy capacity available and the grid operators wish to de-incentivize additional generation of energy from wind turbines and other generators [7]. During these periods of negative electricity value, wind turbine farm operators will often

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