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Modelling of a novel hydro-pneumatic accumulator for large-scale offshore energy storage applications

Daniel Buhagiar*, Tonio Sant

Department of Mechanical Engineering, University of Malta, Malta

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ABSTRACT

Despite the ability of accumulators to smooth out fluctuations in small-scale hydraulic circuits, their use in multi-megawatt power transmission systems remains limited. This is due to the large pressure variations that they experience as their state-of-charge changes when their energy capacity is large. The present work highlights an approach whereby the pressure fluctuations are absorbed by a larger external volume of compressed air. This system has been integrated into a novel floating platform for offshore applications. A thermodynamic model of the gas compression process is developed in order to observe temperature and pressure fluctuations. A brief parametric analysis is undertaken to illustrate the effect of critical system dimensions. This comprises the effect of the external volume with respect to the accumulator volume and the diameter of the umbilical connecting the two components. The system is also simulated in different climates to observe the interaction between the external seawater temperature and the internal gas thermodynamics. A full charge-discharge cycle is simulated and results indicate that around 95% of the energy can be recovered after being stored for a 24-h period. The operational efficiency for a stochastic energy input was also computed and found to be relatively high. Electrical round-trip efficiency was found to be comparable to adiabatic and near-isothermal CAES, but the system can be more advantageous when integrated into the generation-side. The key attribute is the minimization of pressure fluctuations, which results in minimal deviations from the equilibrium temperature. This reduces thermal losses to the surroundings and results in a highly efficient energy storage system.

1. Introduction

Grid-connected renewable energy systems have increased substantially over the past decade. Eurostat data indicates that between 1990 and 2014, total electricity generation from renewables increased by 191% within the EU-28 countries [1]. With the recent agreement at the COP21 climate summit in Paris, the portion of electricity that must come from renewables is set to grow significantly [2].

The issues associated with variable supply, in conjunction with an already variable demand, raise crucial concerns related to intermittency, given that: generation peaks will not match demand peaks. Significant back-up generation is required even if 100% of the power demand can be satisfied through renewables [3]. Energy storage solutions are strong contenders for back-up generation due to their capabilities when it comes to grid stability, load shifting, operational support, as well as overall power quality and reliability [4]. After long disregard, energy storage is making a comeback, thanks to an increasing requirement for its role in adding flexibility, regulating intermittency and providing uninterruptable power [5]. Current trends [6] suggest substantial quantities of energy storage are likely to be deployed in the coming decades.

In islands and coastal regions, offshore renewables will be key contributors to the global energy targets. The numerous advantages of offshore renewables have been well documented [7]. These include better access to natural resources, shorter distances from major population centres, greater capacity factors and increased potential for job creation. Shifting the storage system to the offshore environment also brings with it substantial competitive advantages when collocating systems in a symbiotic way [8], that is, by integrating storage into the structure or support platform of the offshore renewable energy system. This design approach brings with it a cost saving on the infrastructure and also eliminates inefficiencies resulting from having to transmit peak

* Corresponding author.
E-mail address: daniel.buhagiar@um.edu.mt (D. Buhagiar).

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Nomenclature

A_A Liquid piston area [m^2]
A_{umb} Umbilical cross-sectional area [m^2]
$\mathbb{C}$ Air specific heat capacity [Jkg^{-1}K^{-1}]
$Cw_{(i)}$ Wall heat capacity [Jkg^{-1}K^{-1}]
c_p Air specific heat capacity at constant pressure [Jkg^{-1}K^{-1}]
c_v Air specific heat capacity at constant volume [Jkg^{-1}K^{-1}]
D_{umb} Umbilical diameter [m]
E_{adi} Adiabatically-stored energy [J]
e_{umb} Umbilical internal surface roughness [m]
f_{umb} Umbilical friction factor [–]
k_{gas} Gas thermal conductivity [Wm^{-1}K^{-1}]
k_{liq} Liquid thermal conductivity [Wm^{-1}K^{-1}]
L_{gas} Gas portion axial thickness [m]
L_{liq} Liquid portion axial thickness [m]
L_{umb} Umbilical length [m]
$\dot{m}_A$ Mass flow rate of bottom chamber [kgs^{-1}]
$\dot{m}_B$ Mass flow rate into top chamber [kgs^{-1}]
$\dot{m}_{umb}$ Umbilical mass flow rate [kgs^{-1}]
n_s Time-step number [–]
p_{acc} Accumulator pressure [bar]
p_{atm} Atmospheric pressure [bar]
p_{max} Accumulator maximum pressure [bar]
p_{pre} Accumulator pre-charge pressure [bar]
p_A Bottom chamber pressure [bar]
p_B Top chamber pressure [bar]
Q Flow rate of water into bottom chamber [m^{3}s^{-1}]
q_A Heat flux out of bottom chamber to umbilical [W]
q_B Heat flux into top chamber from umbilical [W]
$q_{w,A}$ Heat losses through bottom chamber walls [W]
$q_{w,B}$ Heat losses through top chamber walls [W]
$q_{w,umb}$ Heat losses through the umbilical walls [W]
R Universal air constant [Jmol^{-1}K^{-1}]
$R1_{(i,j)}$ Thermal resistance between the fluid and solid surfaces [KW^{-1}]
$R2_{(i,j)}$ Thermal resistance of the solid wall [KW^{-1}]
$R3_A$ Resistance to heat transfer across the water-air interface [KW^{-1}]
$R_{l/g}$ Resistance to heat transfer between a liquid and a gas [KW^{-1}]
$R_U^{(e)}$ Umbilical elemental thermal resistance [KW^{-1}]
Re Reynolds number [–]
T_A Bottom chamber temperature [K]
T_B Top chamber temperature [K]
T_{amb} Ambient air temperature [K]
T_{dsw} Deep seawater temperature [K]
$T_{in}^{(e)}$ Umbilical elemental inlet temperature [K]
$T_{\infty}^{(e)}$ Umbilical elemental surrounding temperature [K]
$T_{out}^{(e)}$ Umbilical elemental outlet temperature [K]
T_{ssw} Surface seawater temperature [K]
$Tw_{(i)}$ Wall temperature [K]
V_A Bottom chamber volume [m^3]
V_B Top chamber total volume [m^3]
V_{acc} Volume of water in accumulator [m^3]
V_{air} Air volume [m^3]
V_{init} Initial water volume [m^3]
v_r Volumetric compression ratio [–]
$V_{w,A}$ Volume of water in bottom chamber [m^3]
W Work done on the gas [W]
x_i Liquid piston position [m]
γ Ratio of isobaric to isochoric specific heat capacities [–]
η_{elect} Storage system electric round-trip efficiency [–]
η_{gen} Electrical conversion efficiency [–]
η_{hyd} Hydraulic efficiency of the pumping/motoring process [–]
η_{op} Storage system operating efficiency [–]
η_{therm} Storage system round-trip thermodynamic efficiency [–]
μ_{air} Air dynamic viscosity [Nsm^{-2}]
ρ_{air} Air density [kgm^{-3}]

outputs to be stored further down the line. This implies that transmission lines can be sized for nominal as opposed to peak conditions.

Research at the University of Malta in offshore renewables has shown significant benefits resulting from the replacement of the electrical power transmission systems by an open-loop hydraulic circuit using deep seawater [9,10]. The next stage is the development of a storage system that can:

- Exploit the advantages of the offshore environment;
- Integrate into an offshore support structure;
- Interface directly with a hydraulic circuit.

A number of up-coming prototypes have been documented in the open literature, with the objective of satisfying some or all of the criteria above. Some examples are Ocean Renewable Energy Storage [11], Energy Bags for underwater Compressed Air Energy Storage [12], Buoyant Energy Storage [13] and Constant Pressure Accumulators for Offshore Wind Turbines [14]. A common aspect of all these systems is the use of a fluid as the energy storage medium. In the case of a renewable energy system using hydraulic power transmission, fluid-based storage brings with it the potential for direct integration of the storage device [15]. It eliminates the need for an intermediate energy conversion process. One notable example of this is the hydraulic accumulator.

Hydraulic accumulators store small amounts of energy to compensate for fluctuations and short bursts. They are well understood and already widely implemented. Their potential use as direct energy storage devices in hydraulic wind turbines has been identified in a number of publications. Typical hydrostatic circuits utilise a high-pressure line that operates at a fixed pressure [16]. This is analogous to the requirement of a fixed line voltage in electrical power transmission. The problem with integrating an accumulator into the circuit is that as it fills up, the pressure increases exponentially, resulting in a variable pressure circuit (Fig. 1).

The design of a viable constant pressure (isobaric) accumulator for large-scale energy storage applications remains an open design challenge. Presently there is no fully functional system in place. This paper signifies an attempt at developing such an accumulator, exploiting the geometry of a Tension Leg Platform (TLP) and the non-linear relationship between pressure and volume in a compressed fluid. The working principle behind the design is illustrated, along with a detailed thermodynamic model and performance attributes.

2. The proposed system

On observing the non-linear relationship between gas volume and pressure it was noted that for the initial stages of a compression process, the pressure increase is very small for a large variation in volume. Therefore, by limiting the extent of the