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Optimal energy management of an underwater compressed air energy storage station using pumping systems

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ABSTRACT

The paper is part of the development of a novel underwater isothermal Compressed Air Energy Storage (CAES) system. Compared to conventional CAES plant, the performances of this system only depend on the electrical energy required for a round-trip cycle; performances of each sub-system of the power conversion process takes part of the overall efficiency. Consequently, this work is focused on an optimal energy management of the electrical power conversion system driving the isothermal hydro-pneumatic mechanism enabling the air compression/expansion. After examining inherent characteristics of conversion components challenging the overall conversion efficiency, we propose an efficient platform layout based on the segmentation of the energy conversion multiplying power conversion systems with different power ranges. Then, we establish control laws required by the electrical multi-machines system in order to drive pumping systems closed to their best efficiency points. However, these laws subject the conversion platform to a transient and variable operating needing the design of robust controller structures. Finally, we develop a dynamic reversible modelling of the multi-physic conversion platform along with the control scheme. The layout is modelled on Matlab® Simulink® environment and the paper closes with simulation results. We evaluate the dynamic performances of the compressed air storage system in both storage and production mode. Moreover, the effectiveness of power segmentation for the grid integration of the proposed system is discussed.

1. Introduction

For the last decade, power grids have been subjected to rapid evolution caused by environmental issues of historical power sources and a constant rise in energy demand throughout the world. The growth of renewable energy in the world energy mix is still compromised because of the irregularities in power generation. In this way, the energy market is evolving with the development of alternative solutions enabling the expansion of low-carbon technologies in a steady and secured power grid. Considering efficacy and profitability, energy storage systems represent one of the main solutions to support the energy transition [1]. Nowadays, pumping stations lead the storage market and represent more than 95% of the world energy storage. They are mature solutions with massive capacities using natural resources [2]. However, hydropower plants are struggling to develop further because they need specific geological sites with large water capacities [3]. Thus, other natural sources such as compressed air have to be exploited to expand the storage market.

The use of compressed air to store electrical power started in the 1970s. A Compressed Air Energy Storage (CAES) system consists in storing a large volume of air at high pressure in former geological caverns [4]. The principle of storage charging/discharging is separated into the air compression and the air expansion process. The first one performs in storage mode using air compressors where the air compression goes along with heat release. In discharging mode, an air turbine allows for expanding the air while generating electrical energy. A combustion chamber is also required to heat up the air to make the air turbine working feasible. However, the use of a primary resource as fossil fuel leads the storage system to a poor efficiency which limited the development of CAES stations to only two operational storage plants in the world. For instance, to discharge 1 kWh of electrical energy the Huntorf plant needs 0.8 kWh of electrical energy feeding the air compressor and 1.6 kWh of thermal energy provided by natural gas in burn chambers. As for the McIntosh plant, 0.69 kWh of electrical

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Nomenclature

Acronyms

BEP	Best Efficiency Point
CAES	Compressed Air Energy Storage
HP	High Pressure
LP	Low Pressure
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
VSD	Variable Speed Drive
VSI	Voltage Source Inverter

Constants

Φ	electromagnetic flux [V/s]
ρ	sea water density [kg/m^3]
C	DC bus capacity [F]
e	power source voltage [V]
f	mechanical friction [kg/m^2/s]
g	gravity acceleration [m/s^2]
H_{tank}	depth of the tank [m]
J	mechanical inertia [kg/m^2]
L_g	grid inductance [H]
L_s	stator inductance [H]
N	total number of pumps
p	pole pairs number
R_g	grid resistance [Ω]
R_s	stator resistance [Ω]
T_{cycle}	cycle time period [s]
V_{tank}	total volume of the storage [m^3]

Subscripts, Superscripts

*	BEP pump working
0	pump nominal conditions
d	d-axis component
i	iterative number between 1 and N
q	q-axis component

Variables

Ω	pump speed [rpm]
ω_g	grid frequency [rad/s]
ω_s	PMSM frequency [rad/s]
H	pump head [m]
i_g	grid current [A]
i_s	stator current [A]
P	pump pressure [Pa]
Q	pump flow rate [m^3/s]
T_m	motor torque [Nm]
T_p	pump torque [Nm]
U_{dc}	DC bus voltage [V]
V	volume of water pumped [m^3]
v_g	grid voltage [V]
v_s	stator voltage [V]

energy and 1.17 kWh of thermal energy are required. The respective cycle efficiency are 42% and 54% [5]. Finally, storing an amount of grid electrical power requires a higher amount of fossil fuels; the effectiveness of conventional process for electrical storage is questionable considering performances and carbon emissions caused by gas burning.

In the context of renewable expansion, the potential of air as a natural source for massive storage is significant in terms of cost, high power density and scalability of energy storage from domestic utilities to a few GWh applications [6]. Therefore, energetic data mentioned above easily show that a free of gas process must substantially increase the efficiency. Consequently, the main challenge of the current research work consists in removing heat systems based on fossil fuel use. Compared to advanced methods enabling heat recovery through thermal storage [7,8], the configuration called Isothermal-CAES (I-CAES) improves CAES systems without auxiliary storage systems. Air compressors and air turbines conventionally used are replaced by a liquid piston machinery [9]. [10] points out that is one of the most powerful method to compress air, with a compression efficiency up to 95%. Operating in a closed accumulator, an hydro-power system drives the liquid piston to reduce air volume increasing water level; the air pressure thereby increases. Finally, a thermal exchange between the inside and the outside of the chamber is created and attempts to keep air temperature closed to the surrounding temperature during charging and discharging mode. More details about liquid piston sizing and optimisation for isothermal performances are given in [11,12]. The overall efficiency of I-CAES technology is generally up to 70% [13–15]. Compared to CAES system, the primary energy source required to produce electrical energy with an I-CAES plant comes exclusively from the grid electrical power because the storage is now free of gas requirement. As a result, the round-trip conversion efficiency depends directly on the ratio of the amount of the electrical energy to be discharged on the energy needed for charging [16]. Numerous studies show that the main problem of maximizing the energetic efficiency of I-CAES system is no longer in the compression process itself but in minimizing energy losses of each of the elements of the conversion platform driving the hydro-pneumatic device enabling the air compression/expansion [17–19].

Finally, beyond that CAES performances must be improved, the compressed air storage in rock caverns constrains geological implantation. In 2016, the French environmental public institution demonstrated that CAES capacity could store around 5 TWh per year of energy but it only represents 1.5% of annual renewable production expected by 2020 [20]. Consequently, marine environment is studied for large-scale storage. As well as the massive implantation potential, [21] shows that the use of seawater to storage isobaric large volume of air is more efficient ans scalable than underground CAES.

This paper focuses on developing a efficient methodology optimizing the electrical power conversion sub-system in order to maximise performances of a new underwater I-CAES plant in preparation of marine energy spreading. The paper is organized as follows: the proposed storage plant is describes in Section 2, Section 3 details the power conversion process allowing for charging/discharging mode. Section 4 is focused on energy conversion management strategy minimizing energy losses of sub-systems. Mathematical modelling of power conversion devices and control structures are established in Section 5. Finally, results from some test simulation of a small scale case study are presented in Section 6.

2. Description of the proposed underwater I-CAES system

The proposed I-CAES plant operates in marine environment. The system is developed by the company Segula Technologies for storage density of a few hundred MWh of electrical energy in prospecting for local-scale grid support of electrical power produced by offshore farms. It is composed of two distinct parts, a floating platform and an underwater storage tank tied up in the ocean floor, Fig. 1.

The floating platform is connected to both the power grid through a submarine electrical cable and the storage tank by a pneumatic link. It