Compressed Air Energy Storage for Offshore Wind Turbines

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ABSTRACT

Integrating renewable energy sources, such as offshore wind turbines, into the electric grid is challenging due to the variations between demand and generation and the high cost of transmission cables for transmitting peak power levels. A solution to these issues is a novel high-efficiency compressed air energy storage system (CAES), which differs in a transformative way from conventional CAES approaches as it employs near-isothermal compression/expansion and energy storage prior to conversion to electrical power. This approach utilizes seawater as a liquid piston for air compression. The liquid piston creates a positive gas seal, enables a high surface area compression space for increased heat transfer, and utilizes the ocean as a thermal source/sink. The compressed air is stored in an "open accumulator," where the air volume is modified through displacement of a liquid. The ability to exchange energy in the open accumulator by addition or subtraction of the gas or the liquid provides system control advantages, including storage of high power transients and direct control of air pressure independent of the energy storage level. Following a presentation of the system, the authors present a sizing example and a discussion of future work required for realization of this promising technology.

1. INTRODUCTION

Integrating renewable energy sources into the electric power grid is important to reducing the consumption of fossil fuels and corresponding greenhouse gas emissions. A current goal is to derive 20% of the nation's energy from wind power by 2030 [1]. Offshore wind power is especially promising due to high class wind zones existing near areas of high population density. Further benefits of offshore wind power include the ability to ship and construct larger wind turbines, compared to land based turbine projects, and reduced human objections to noise and view by positioning them sufficiently off shore.

A major challenge of integrating wind and solar renewable energy sources into the electric power grid is the inconsistency of renewable power generation due to variations in wind speed and solar intensity. Furthermore, diurnal power consumption variations are not aligned with renewable power generation. These two factors result in the need for fossil fuel based power generation systems that meet higher levels of power variation and rapid ramp rates such as gas turbine fired power plants instead of less expensive base load generation systems, such as nuclear and large coal fired or co-generation power plants [2].

To ease the power demand and supply variation challenge, energy storage can be added to the power grid to store energy during periods of high production and low consumption, and release energy during periods of low production and high consumption. Many energy storage technologies exist, including pumped hydro, compressed air energy storage, a variety of battery chemistries, capacitors, flywheels, thermal storage, and more exotic technologies such as super-conducting magnetic energy storage. The topic of this paper, compressed air energy storage, is highly scalable, reasonably inexpensive, provides moderate ramp rates, and potentially highly efficient.

Conventional compressed air energy storage (CAES) systems utilize electric power during off-peak hours to compress air up to 7 MPa in an adiabatic air compressor and store the air in underground salt caverns. During peak power demand periods, the compressed air is expanded in a natural gas fired turbine. Two such facilities currently exist, including a 290 MW facility in Huntorf, Germany and a 110 MW facility in McIntosh, Alabama, and other CAES plants are under development, including the Iowa Stored Energy Park and a facility in Norton, OH [3)].

While conventional CAES systems are economical and provide utility scale storage capacity, the system efficiency is low, primarily due to the thermal energy losses in intercoolers, required to cool the air to a reasonable temperature levels for underground storage. While conventional CAES system efficiency has been debated due to the added energy of natural gas during expansion, many estimates of efficiency are near 50% [4)]. An additional drawback of conventional CAES systems is the variation in power input or output with reservoir pressure, limiting the allowable energy storage to maintain a desired pressure ratio.

In contrast to conventional CAES, a new method is proposed where each offshore wind turbine is equipped with an isothermal CAES system that stores energy prior to conversion to electric power and recovers energy without combustion of a fossil fuel. This approach accommodates the daily variations in energy supply and demand, proving load shifting. Furthermore, by locating the energy storage device at the offshore wind turbine, the electrical collection and transmission lines can be downsized to meet the average power production instead of the peak power production. For offshore wind farms, the collection and transmission system is approximately 15% of the total farm cost [5)]. In a class 6 wind zone with a 47% capacity factor [6)], the collection and transmission system cost can be reduced approximately 20% by transmitting the average power instead of the peak power [7)]. Similarly, the electric generator at each wind turbine can be downsized to near the average power, providing further cost savings.

This paper presents the concept of an isothermal compressed air energy storage system for offshore wind turbines that utilizes an open accumulator [8)] to manage the air pressure independent of the quantity of energy stored. The system architecture is first presented in section 2. In section 3, the isothermal liquid piston compressor/expander concept is explained. The open accumulator behavior is presented in section 4, followed by a sizing example in section 5, and concluding remarks in section 6.

2. SYSTEM ARCHITECTURE

The isothermal compressed air energy storage system, depicted in Figure 1, utilizes a significantly different drive train than a conventional wind turbine. In the nacelle of the wind turbine, the shaft driven by the turbine blades is directly coupled to a variable displacement hydraulic pump, moving all other major components to the surface level. This change eliminates the costly, heavy, and failure-prone gearbox that is used in conventional wind turbines to couple the turbine shaft to the electric generator [9)]. The hydraulic power created by the pump in the nacelle drives the hydraulic transformer. The hydraulic transformer supplies flow to, or receives flow from, multiple liquid piston compression/expansion chambers and drives the electric generator. In the liquid piston chambers, which will be discussed in more detail in the next section, the liquid from the hydraulic transformer is in direct contact with the air, providing compression or expansion. Valves at the top of the liquid piston chambers control airflow in and out of the liquid piston chambers. For example, during compression, air is drawn into the compression chamber from atmosphere as the liquid piston is retracting, the valve to atmosphere is closed, and the liquid piston compresses the air near-isothermally until the valve to the open accumulator is opened and the air is pumped into the open accumulator. The behavior of the open accumulator will be further explained in section 4.

The liquid in the compression/expansion chambers, water in this case, provides the primary thermal transport path into and out of the system. Instead of employing a heat exchanger for transferring heat to and from atmosphere, the water is directly drawn or discharged to the ocean or lake, utilizing the water body as a thermal source/sink. Utilizing seawater hydraulics introduces challenges in the areas of filtering, tribology, and sealing. Despite these challenges, the benefits to heat transfer and of environmentally benign leaks are extremely beneficial for this “green” technology.

As previously mentioned, implementing compressed air energy storage at each wind turbine enables transmitting the average power instead of the peak power. In contrast to a conventional wind turbine of the same power rating, the electric generator in the proposed system can be significantly downsized. Furthermore, the hydraulic transformer can be designed to maintain a constant generator shaft speed, enabling use of a synchronous AC generator, further reducing cost in comparison to asynchronous generators that require expensive power electronics.

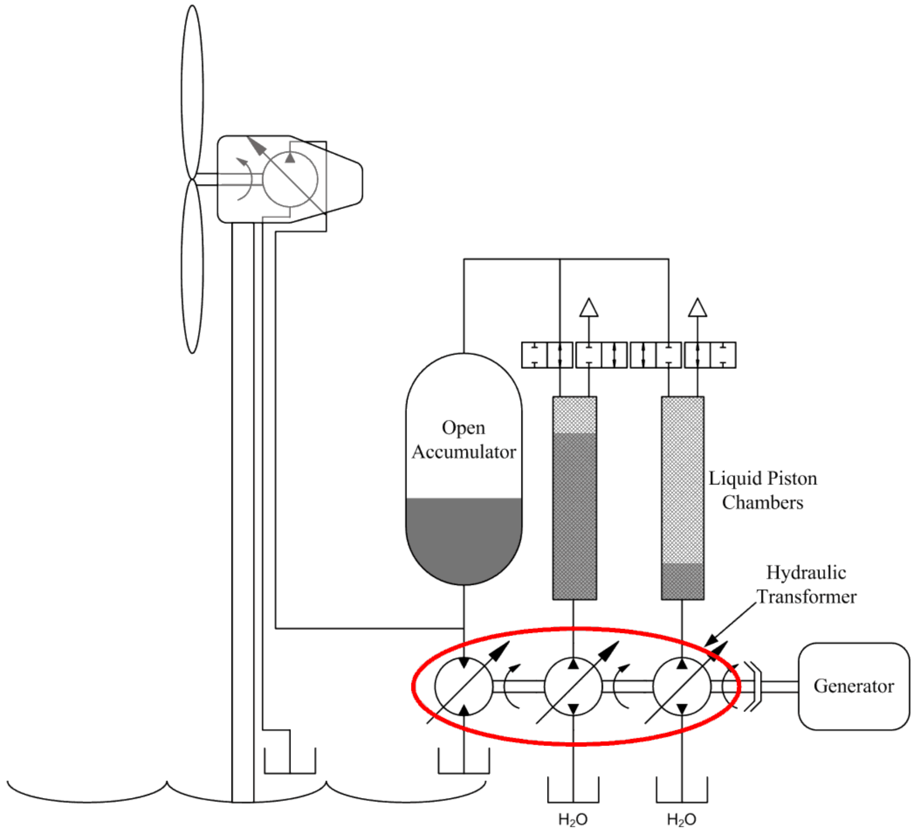

Figure 1 Compressed air energy storage system with the open accumulator coupled to an offshore wind turbine.

3. LIQUID PISTON COMPRESSION/EXPANSION

A key feature of the proposed compressed air energy storage system is isothermal compression/expansion. In conventional positive displacement compressor/expander architectures, such as a mechanical piston in a cylinder, the surface area to volume ratio is low. A low surface area to volume ratio results in poor heat transfer, and thus a large percentage of the piston work results in increasing the internal energy of the air, which is later lost in intercoolers or in the storage vessel. Contrary to a mechanical piston that requires a specific geometry to enable piston ring sealing, a liquid piston is able to conform to an irregular volume. This allows the surface area in the compression/expansion chamber to be dramatically increased, improving heat transfer. Surface area features can range from a fine wire mesh, to many small diameter cylinders, to vertical plates, to other features. Since the temperature range during operation is small, heat pipes may also be considered. A diagram of the liquid piston compression/expansion chamber utilizing vertical rods as surface area elements is presented in Figure 2.

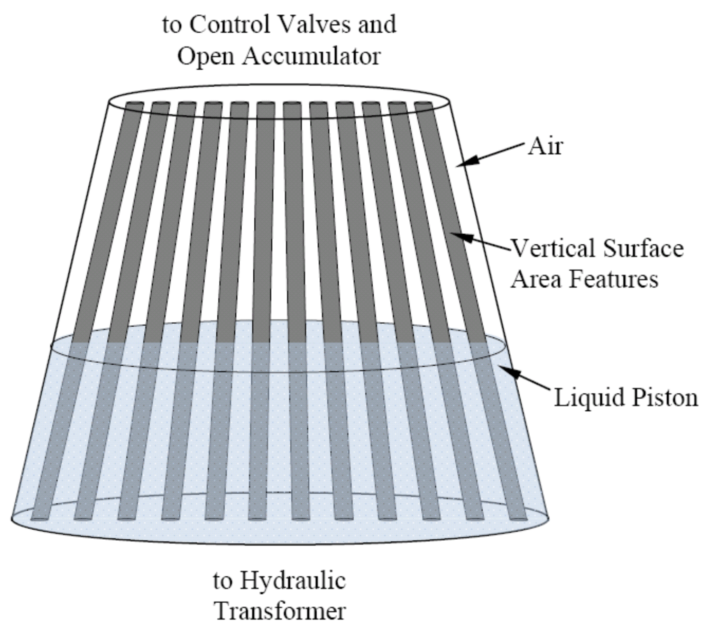

Figure 2 Liquid piston compression/expansion chamber with a schematic of the surface area features used to augment heat transfer.

To understand the thermal transport in the liquid piston chamber, consider a compression stroke. As the liquid piston extends and compresses the gas, the air transfers heat to the surface area elements, which provide a temporary thermal storage. As the liquid displaces the air, it comes into contact with the surface area elements, absorbing heat. During retraction of the liquid piston, the heated liquid is exhausted to the ocean or lake. The cycle then repeats. During expansion, the opposite process occurs where the liquid is used to heat the surface area elements and then the gas. Previous studies by the authors have found that the heat transfer rate can be improved by two to three orders of magnitude at the same operating frequency by utilizing a liquid piston instead of a mechanical piston [10; 11].

In addition to improving heat transfer, the liquid piston provides additional benefits. First, the liquid piston creates a positive seal, eliminating air leakage past mechanical seals, which is especially important at high pressure. Second, the liquid piston eliminates the sliding friction of a mechanical piston. It must be noted that this sliding friction is replaced by viscous friction of the liquid piston moving past the surface area elements. Third, due to the elimination of sliding friction, the wear in the compression/expansion chamber is decreased dramatically. Finally, the liquid provides a thermal transport path into and out of the chamber, eliminating the need to transfer heat through the chamber wall. An alternative or complementary method of enhancing heat transfer is to inject small water droplets into the compression/expansion chamber, further improving the surface area.

Because the hydraulic transformer drives the liquid piston, the displacement profile of the piston is infinitely variable. The piston displacement profile greatly influences the trade-off between compression efficiency and operating frequency. As found by Sancken and Li [12], utilizing a high piston velocity during the initial stages of compression and a lower velocity at higher pressures enables up to a 500% increase in compression frequency with the same efficiency, as compared to a sinusoidal piston displacement profile. Specifically, for a compression/expansion chamber with a given heat transfer capability (i.e. the product of heat transfer coefficient and surface area) the optimal compression or expansion trajectories that minimize the process time (hence increasing power) for a given thermodynamic efficiency consist of an adiabatic portion followed by an isothermal portion, and then another adiabatic portion. A challenge of implementing aggressive piston displacement profiles is that the hydraulic transformer must operate at low fractional displacements for a large portion of the stroke, which is a region of low efficiency for conventional hydraulic pump/motors.

4. OPEN ACCUMULATOR

In conventional CAES systems, the air storage vessel is a fixed volume and contains only air, resulting in the air pressure increasing with increasing energy stored. To maintain a desired power range for the compressor/expander, the pressure must be maintained within a specified range, resulting in a decrease in useable energy. In the proposed "open accumulator" approach, the storage vessel contains both air and liquid, where the liquid is used to change the volume occupied by the compressed air [8]. The open accumulator provides two energy storage branches, the energy dense pneumatic branch and a hydraulic branch that is efficient and power dense. A simplified circuit diagram of the open accumulator is presented in Figure 3. It should be emphasized that the air compressor/expander in the figure is realized with the liquid piston compression/expansion chambers in the proposed system.

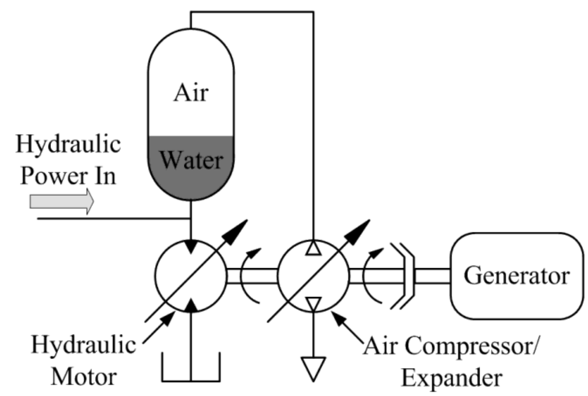

Figure 3. Schematic of the open accumulator concept. Note that both the liquid and the air can be added or removed from the vessel independently, enabling pressure control.

The primary benefit of the open accumulator over a conventional air storage vessel is that the air pressure is independent of the quantity of energy stored. To illustrate the operation of the open accumulator, consider the case where energy is being stored from a low state of charge, which is characterized by the open accumulator being primarily filled with liquid. As energy is added at a low power level, compressed air is added to the open accumulator and liquid is removed through the hydraulic motor at a rate that maintains a constant pressure. The hydraulic motor power created by removing liquid from the accumulator is used to drive the air compressor. During extraction of energy, this process is reversed where air is removed from the open accumulator and liquid is added.

The open accumulator provides additional benefits beyond pressure regulation. First, due to the order of magnitude higher power density of hydraulics over pneumatics [13], during high-power transient events, energy can be added or removed simultaneously with both the hydraulic and pneumatic branches at the expense of not maintaining pressure. Because high power transients can be managed with the hydraulic branch, the air compressor/expander can be downsized to meet the mean power and not the peak power. Second, as previously discussed, utilizing sea or lake water in the liquid pistons is highly desirable from an environmentally conscious point of view. By also utilizing water hydraulics in the open accumulator, water from the liquid pistons that mixes with compressed air will simply be deposited in the liquid column of the open accumulator. This eliminates the need for complex water/air separators and auxiliary means of draining water from the air storage vessel.

5. SIZING EXAMPLE

To illustrate the behavior of the compressed air energy storage and open accumulator system for an offshore wind turbine, a simple sizing example is considered. Consider storing all of the energy from a 5 MW wind turbine that is generating an average of 3 MW for an 8 hours period, resulting in 86 GJ of energy. Assuming isothermal compression, which will be approached in the liquid piston chambers, and assuming that the air behaves as an ideal gas, the compression work can be expressed as:

$$W = -\int_{V_{exp}}^{V_{comp}} \left(P - P_{atm}\right) dV \qquad (1)$$

$$= P_{atm} V_{exp} \left(\ln|R| + 1/R - 1 \right) \qquad (2)$$

where Vexp and Vcomp are the expanded and compressed volume of air respectively, Patm is atmospheric pressure, and R is the compression ratio, defined as the compressed pressure divided by atmospheric pressure. If the compressed pressure is set to 35 MPa, creating a compression ratio of 347, the expanded volume of gas that must be compressed is 176,350 m3, resulting in a compressed volume of 509 m3. If the open accumulator is spherical in shape, the inner radius required to store this volume of air is 4.95 m. For reference, a commercially 5 MW wind turbine has a 126 m rotor diameter and a tower height of 100+ m. The air storage vessel is proportioned such that it can be integrated into the structure of the tower or used as ballast in a floating wind turbine design.

Because the internal energy of the air during compression remains constant due to the isothermal assumption, the work done on the system must equal the heat transfer out of the system. If the operating frequency of the liquid pistons is 1 Hz and the cycle is equally split between compression and fresh air intake strokes, the average heat transfer rate during each compression stroke is 6 MW. If further assumptions are made of a convective heat transfer rate, h = 100 W/K/m2, and a temperature difference between the gas and the interior of the compression chamber, ΔT = 5 K, then the required surface area for heat transfer is 12,000 m2. For this same operating frequency, the volume of air at atmospheric pressure displaced by each cycle of liquid piston is 6.12 m3. Thus, the required surface area to volume ratio to achieve the required heat transfer rate is 1960 m-1.

As discussed, a large surface area to volume ratio in the liquid piston chambers can be created through a large variety of geometries. One option, shown in Figure 4, is to utilize many uniformly spaced small diameter rods that are orientated vertically in the chamber. By assuming that the influence of the boundaries of the chamber is negligible, the surface area to volume ratio can be calculated by dividing the geometry into a series of equilateral triangles, as shown in the figure. By assuming a unit length and recognizing that triangle contains 1/6 of each of the three circles at the endpoints, the volume of fluid within the triangle can be described as:

$$V = V_{triangle} - V_{rods} = \frac{\sqrt{3}}{4} l^2 - \frac{1}{2}\pi r^2 \qquad (3)$$

where l is the distance between the rods and r is the radius of the rods. By again assuming a unit length, the surface area of the rods within the triangle is described by:

$$A_s = (3)\left(\frac{1}{6}\right) 2\pi r = \pi r . \qquad (4)$$

It must be noted that the surface area changes throughout the stroke as the air occupies a smaller volume of the compression chamber, warranting caution of the simplification in Eqn (4). The surface area to volume ratio is described as:

$$\frac{V}{A_s} = \frac{\pi r}{\frac{\sqrt{3}}{4} l^2 - \frac{\pi r^2}{2}} \qquad (5)$$

If the distance between the rods, l = 3r, then the rod diameter to achieve the required surface area to volume ratio is 1.4 mm.

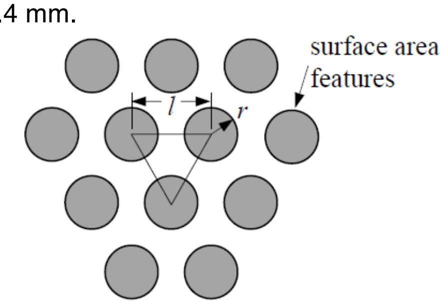

Figure 4. Top view of a portion of the liquid piston chamber, which utilizes an array of small rods to increase the surface area to volume ratio.

While the above sizing example presents a single stage compression, a multiple stage compression is likely a better solution. A prime benefit of utilizing multiple stage compression is an improvement in heat transfer at higher pressures while minimizing the total drag forces. In a multiple stage compression where each stage has the same compression ratio, the work in each stage is approximately equal, and thus, the required heat transfer is equal. However, the volume of the higher-pressure stages are smaller, resulting in higher surface area to volume ratios in higher-pressure compression stages. The reason for not utilizing the higher surface area to volume ratio throughout all stages is that the higher surface area elements will increase the viscous drag forces. Thus, the higher surface area to volume ratio should only be applied where needed. It should be noted that a single stage liquid piston chamber could be designed with an increasing surface area to volume ratio with percentage of compression stroke, but this would require significant complexity. An additional benefit of utilizing multiple stages is a higher average fractional displacement of the hydraulic transformer, improving efficiency and control over the displacement profile.

6. CONCLUSION

The novel compressed air energy storage system presented in this paper is an efficient method of storing energy to ease the integration of renewable energy sources into the power grid. The advantages of the proposed system over conventional CAES systems include higher efficiency due to near isothermal compression/expansion, storage of energy prior to conversion to electrical power, and elimination of combustion of natural gas during energy recovery, creating an environmentally benign solution. While the discussion has focused on off shore wind turbines as a potential application, the system can also be applied in numerous other areas of the power grid.

The efficiency improvements of the novel CAES system are largely due to the liquid piston compression/expansion. The ability of the liquid piston to fill an irregular volume allows increasing the surface area of the compression/expansion chambers to approach near-isothermal behavior. Furthermore, the liquid piston eliminates air leakage past a mechanical piston and eliminates mechanical friction, while introducing viscous drag.

The proposed system decreases the cost of offshore wind systems in multiple ways. First, by utilizing a hydraulic drive train between the wind turbine and the hydraulic transformer, the gearbox is eliminated, reducing nacelle weight and cost, while improving reliability. Further cost benefits are created by downsizing the electric collection and transmission system and the AC generator by transmitting the average power instead of the peak power. In addition, the constant shaft speed of the hydraulic transformer allows use of a synchronous AC generator, eliminating costly power electronics used for asynchronous systems.

Utilizing the open accumulator for the liquid piston CAES system creates multiple performance benefits over conventional CAES. Through control of the hydraulic and pneumatic flows, the air pressure becomes independent of the quantity of energy stored. This maintains constant power capabilities during all conditions and improves energy density. The addition of the hydraulic branch also creates an efficient method of sinking and sourcing high power transients, allowing downsizing of the liquid piston air compression branch.

The simple sizing example demonstrated that the scale of the system is reasonably proportioned for an offshore wind turbine. The ~500 m3 open accumulator vessel can be integrated into the structure of a sea-floor anchored turbine tower or used as ballast for a floating wind turbine. The air flow rate of 6.12 m3/s standard (atmospheric pressure and temperature) is large, but achievable with multiple liquid piston chambers operating simultaneously. As discussed, it is beneficial to use multi-stage compression for the purpose of tuning the liquid piston chambers for heat transfer by provide a higher surface area to volume ratio at higher pressures. The multiple stage approach also increases the average displacement of the hydraulic transformer, improving efficiency and control resolution of the liquid piston displacement profile.

While this paper has outlined the liquid piston CAES and open accumulator concept, much future work is required to realize this promising technology. Future work includes modeling of the fluid dynamics and heat transfer within the liquid piston chambers. Beyond creating a balance between increasing the heat transfer and maintaining suitable viscous losses, design for suitable the cycle frequency and liquid-gas interface stability must be addressed. In addition, the kinematics, tribology, and machine design in the hydraulic transformer must be studied and designed for high efficiency across a large range of fractional displacements and for seawater operation. Finally, the overall system must be optimized for performance and efficiency and control methods must be developed. This system has the potential to provide a cost-effective, efficient, energy-dense, and power-dense energy storage system capable of performing in many environments, including the open ocean.

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