International Journal of Electrical Engineering & Emerging Technology, Vol. 01, No. 01, DEC 2018, pp 1-6

Design and Implementation of Pumped-Hydro-Compressed-Air Energy Storage System

Rohit Kumar[1*], Abdul Wahab[1], Wajid Ali[1]

[1] Department of Electrical Engineering, Mehran University of Engineering and Technology, Jamshoro, Pakistan
Corresponding authors e-mail: abdulwahabmalik@ymail.com
[**Received on:** 02-11-18 **Accepted on**: 28-11-18 **Published on:** 05-12-2018]

***Abstract*— The need for bulk energy storage systems has arisen due to the unreliable nature of the alternate energy generation. Currently, two energy storage systems are being employed around the world for bulk power storage, which are Pumped-hydro energy storage (PHES) and compressed-air energy storage (CAES) systems. But, due to their dependency on geographical location, these two systems cannot be used with all power generation systems. Another the system has recently been introduced that combines the advantages of both PHES and CAES system known as Pumped-hydro-compressed-air (PHCA). The main advantage of the PHCA system over the other two is independence from the specific geographical locations and compactness.**

In this paper, the working model of the PHCA system is designed that stores the potential energy in the form of water and air pressure; the water is stored at the pressure of 500 psi. The PHCA storage system starts generating the power during outages and power variations in the main generation system. The working model of the PHCA system confirms that the idea of PHCA is very practical and can be used in various power plants to store electrical energy in bulk quantity.

***Index Terms* — Energy Storage, PHCA, Potential Energy, Power Generation.**

I. INTRODUCTION

Energy plays a vital role in the progress of any country hence it must be conserved in a most efficient way. Not only the technologies should be developed to produce clean and reliable energy from all the available resources, but enough importance should be given to efficient conservation of energy so that reliability of generation system could be improved. The use of renewable sources is considered to be the more viable option for addressing the energy needs. But these independent renewable energy sources cannot be relied completely to produce continues power. Hence there is a need for energy storage system that will store the energy in an efficient and reliable way. So far two technologies PHES and CAES have proved efficient to store the energy in the bulk quantity, but there are various problems associated with these systems so currently, the most feasible and viable technology available for energy storage is PHCA (Pumped Hydro Compressed Air) Energy Storage. This special system makes use of Water and Compressed Air to store the energy reliably. The PHCA energy storage technology enables the storage of energy in a bulk quantity and an efficient manner. The addition of PHCA storage technology can improve the overall efficiency and reliability of the power system. The PHCA energy storage technology can be implemented on large scales as well as on small scale. The main purpose of developing the working model is to demonstrate the idea and feasibility of the PHCA energy storage system.

II. PROBLEM ADDRESSED

The conventional methods of bulk energy storage systems including PHES and CAES are very expensive and highly dependent on geographical location. The use of alternate energy generation fails to provide high reliability alone due to various factors. So, there is a need to use an energy storage system that should be reliable, durable, and independent of geographical location. The more suitable energy storage system that fulfills all the above requirements is PHCA energy storage. The PHCA is being designed and analyzed in this research work.

III. CHALLENGES IN DESIGN AND CONTROL

Generally, the PHCA setup was not easy, faced different challenges during the modeling of this transactive system. The faced difficulties were mainly related to unavailability of equipment's of needed ratings like unavailability of the motor that can pump water at 500 psi, so it was needed to choose an alternative of utilizing the simple pump to transfer the liquid at 0 pressure thus creating problems in the system. The other major problem was the unavailability of the tank that can store water at such high pressure, so it was needed to build a tank having an extra coating. The unavailability of Automatic control valves of needed ratings also created huge problems as they were available in higher ratings of voltage.

IV. BACKGROUND AND RELATED WORK

The first approach to new storage system PHCA (Pumped Hydro Compressed Air) is discussed in [1]**.** The paper [1] briefly explains the PHCA storage system, its parameters, its

working principle, its characteristics, the working stages. Another improved approach to PHCA system is discussed in [2], which presents a modified form of PHCA system known CPPHCA that uses separate tanks for storing water and compressed air respectively.

There are various bulk energy storage systems used world widely. One such energy storage system is a PHES, Pumped Hydro energy storage is a mature technology for storing electrical power as it acquired the first rank in the international market for energy storage [3] [4]. However, the PHES system possesses some drawbacks too. The main drawbacks of this technology are a requirement of large initial investment, long construction time and being easily affected by topology. Moreover, its influence on regional ecology and geology has largely affected its progress as an energy storage system. The PHES is only suitable for large scale-based usage. Owing to its characteristics this PHES technology is being limitedly adopted in the world for the energy storage. [5] [6]. The other mature energy storage system is CAES. Initially, this technique was introduced by German in the late 1970s and 1980s. The First CAES station was established in Germany as a demonstration project, which is still in operation today. The CAES technology also faced some technical deficiencies especially the issues related to feasibility of the CAES station which was investigated [7], [8], [9] [10] [11] [12], the biggest flaw continues to remain there in CAES system are, its complex design, heavy investments, and its expensive equipment's such as heat exchanger caused the huge problems for the investors in adopting this technology.

V. PUMPED-HYDRO-COMPRESSED-AIR (PHCA) ENERGY STORAGE SYSTEM

Pumped Hydro Compressed Air (PHCA) is a newly emerged bulk energy storage technology which is an integrated version of the two previously known energy storage systems, the CAES and PHES. By integrating both energy storage system the disadvantages of both the systems are countered and energy can be stored at the maximum efficiency.

This new idea of bulk energy storage evolved from China as it faced tremendous fall back in their energy sector due to the wastage of their wind energy. The wind power generation in China rose to 17% of the total generated by wind farms [13, p. 1]. The wastage was due to the generation capacity of China wind farm exceeded the demand capacity. In the year 2013, China's wind power generation exceeded more to 15TW.h. [2], and it is expected to increase more in the coming future with further expansion of wind farms in China. Certain arrangement to store electrical power can increase the effectiveness in the power system by storing excess energy and releasing it during power consumption peaks. [14].

A. Working Principle

This more efficient storage system employs the basic principles of both PHES and CAES energy storage system. It utilizes the water and compressed air to store the energy in the form of potential energy. The water is used as working fluid and compressed air is used to give this water a virtual height so to raise its pressure. The water with pressure strike on the turbine which causes it to rotate and generate electricity.

The basic principle can be illustrated as: assume an airtight vessel that is filled with air at high pressure with the help of a compressor. This airtight vessel is also connected to a high-pressure water pump through a pipe. The water pump delivers the water to the airtight vessel from another tank placed at lower level. As the pump starts to fill the airtight vessel with water, it constitutes a virtual height in the vessel due to high pressure of the air inside. For the rise of every 5 MPa of pressure, a virtual height of 500 meters is obtained. For example, if the pressure inside the airtight vessel is raised to 15 MPa, it will be equivalent to the water stored at a height of 1500 meters.

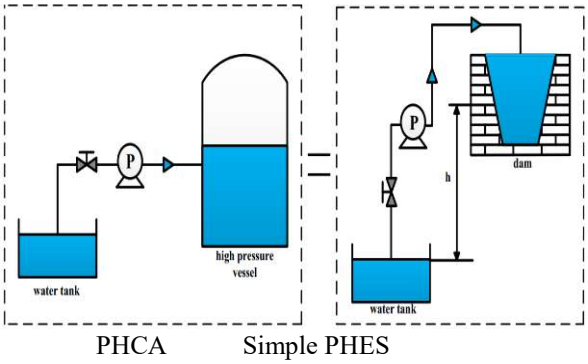

Fig. 1. Basic Model of PHCA

Fig. 1 compares the two storage systems, i.e. PHCA and PHES. In PHCA system, the pressure vessel is used which contains pressurized air and water. Whereas in PHES system, simple water storage tank is used. The basic model of PHCA storage system is comprised of airtight vessel, lower water storage tank, high-pressure water pump, air compressor, hydel turbine, electric generator, and control scheme [15]. The flow of the water to hydel turbine is controlled by changing the position of the valves with some control scheme. As the water in the tank decrease due to the generation of electricity, the pressure inside the pressurized vessel will decrease. As a result, the flow of the water will decrease and the generation of power will also be reduced. For stable operation of PHCA system, it is necessary to keep the pressure of the pressurized vessel constant.

B. Practical Model

The PHCA energy storage system is equipped with water pump that connect an upper high-pressure vessel to a lower water tank. During the off-peak period, the cheaper power from the main supply is utilized to pump the water from lower water tank to the high pressurized vessel. As a result, the energy is stored in form of potential energy. During the peak hours, this stored potential energy is utilized as kinetic energy to move the turbine. For this, the water from high-pressure vessel is allowed to fall on the blades of the turbine to generate electric power.

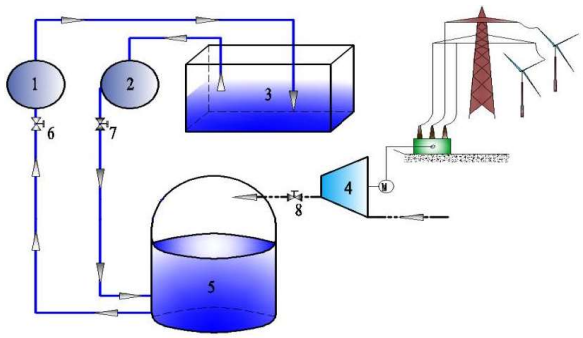

Fig. 2. A practical model of PHCA

As from the Fig. 2, initially, the pressure is raised of the high-pressure vessel (5) to certain required level with help of compressor (4), which is driven by the main source. The compressor only works during the initial period to create the initial pressure. For storing the energy, the water is injected through a pump which shifts water from the lower reservoir to the main vessel. This pump extracts power from the main source when the required level of water is achieved this pump is turned off. The energy is stored as the potential energy. This is the same as giving the dam a virtual height to raise its potential energy. (P.E = mgh). At this point, the energy storing process is completed.

For the energy generation process, the water from the upper reservoir strikes the turbine. This high pressurized water moves the hydro turbine which power the generator and the electricity is generated. The water excreted from the turbine moves to a lower reservoir for the next cycle. This cycle continues, and energy is being stored during off-peak hours and utilized during peak time.

C. *Characteristics of the PHCA System*

PHCA possesses better characteristics to store the energy compared to other storage systems. The second law of thermodynamics describes that, thermal energy is not completely convertible to mechanical energy because some of the thermal energy is lost. But a transfer to object processing lower temperature can be transferred to thermal energy completely [16]. The empirical studies show that mechanical energy possesses the highest quality than any other energy [16]. The mechanical energy has a large number of applications. In this new PHCA system, the energy from mechanical energy (potential energy) is converted into the electrical energy by using hydel turbine. Thus, it can be inferred theoretically that, PHCA system has higher energy utilization than CAES and PHES in terms of energy quality [1].

It has got several advantages as compared to the other two systems:

- Simple design and construction: In this facility, the heavy equipment such as heat exchangers, cooling equipment are not required.
- High overall efficiency: The high-pressure water pump and hydel turbine have far better efficiencies than the compressor and expander used in the CAES system.
- Less Costly: The use of low-cost equipment makes it economical than CAES and PHES systems.
- Independent of specific geographical locations
- It has the advantage of low water supply needed and water storage density and capability can be easily changed.

VI. PERFORMANCE STAGES IN PHCA SYSTEM

There are three main stages in the PHCA system, which are:

A. *Initial Compression Process*

The first stage of storing energy in a PHCA system is to supply the pressurized air to the vessel with the help of a compressor. The air should be injected in advance to the vessel because air is filled once in the high-pressure vessel and is not allowed to go out. The compressor that is used to fill the air has low flow rate, it is useful for increased efficiency of the system.

B. *Water Injection Process*

In this process, the water is fed to the high-pressure vessel by the water pump. The increase in the water level inside the pressure-vessel also increase the pressure of the air, hence by this the required level of volume is achieved in the vessel and the energy is stored in the form of potential energy.

C. *Power Generation Process*

In this process, the water at high pressure is discharged through the hydel turbine to rotate its blades. As a result, the power is generated. The pressure is kept constant during the whole process.

VII. EXPERIMENTAL SETUP

The PHCA Energy storage system consists of two tanks as shown in Fig. 3, the upper one and lower one. The upper tank consists of compressed Air and water. Initially, the motor pumps water in the upper tank, upon reaching the desired level the motor is turned off. Then the compressor starts filling the high-pressure air in the tank. The motor and compressor are driven by the excess energy from the main supply source during off-peak hours. The energy is stored in the form of potential energy which is utilized in running the load during peak hours. The PHCA start supplying energy to the loads by allowing the stored high pressurized air and water to strike on a hydro turbine thus generating the electricity. The energy is tapped from the turbine and supplied to loads. This cycle continues, and the system works in the closed cycle. The pressure is kept constant in the tank and the water excreted from the turbine is stored in the lower reservoir. The generation of energy depends on the potential energy stored in the tank. The parameters of the system can be varied to optimize and get the desired output.

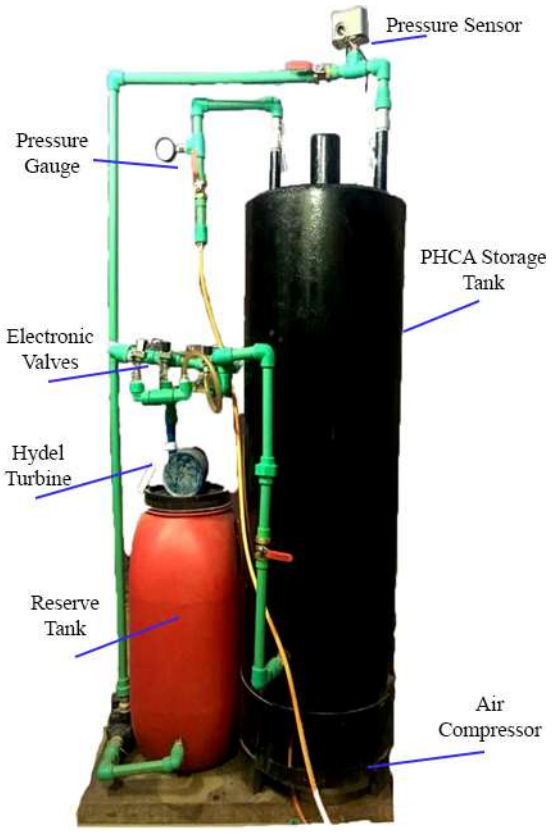

Fig. 3. The PHCA Energy Storage System

In the working model, the upper storage tank has the capacity of 50 gallons of which around 15 gallons are consumed in storing the water and rest is consumed in storing the compressed air. The compressed air's pressure is set up to 500 psi, which can be increased to store more energy. As the tank is filled with the water and compressed air, in this way energy is stored, this high pressurized water and air have the potential to generate the electricity. The water combined with a high pressurized air strike on the turbine and the potential energy is converted into mechanical energy that drives the turbine and electricity is generated. The parameters and rating of the components used in the PHCA system are shown in Table I.

TABLE I
PARAMETER OF MAIN COMPONENTS OF PHCA SYSTEM

Component	Quantity	Set Value [a]
PHCA Tank	Pressure	500 psi
	Total Volume	200 Liters
	Air/Water Ratio	140:60
Hydel Turbine	Rated Power	120 watts
	Rated Voltage	12 volts
	Rated Current	10 Amps
	Speed	1500 rpm
Water Pump	Rated Voltage	220 volts
	Rated Current	1.7 Amps
Compressor	Rated Voltage	220 volts
	Max Pressure	500 psi
	Rated Power	500 watts

A. PHCA Control Circuit

The control circuit shown in Fig. 4 controls every operation of the system. It is ATMEGA328P-PU microcontroller based which commands different equipment to perform the designated operation in the system. The hardware implementation of control circuit is shown in Fig. 5.

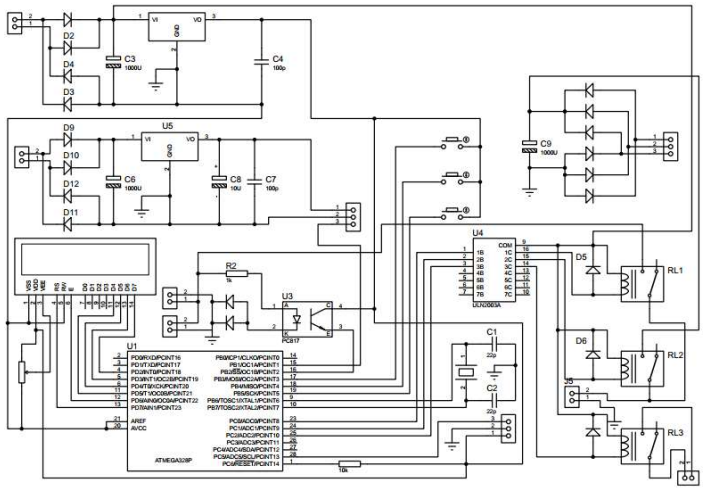

Fig. 4. Schematic diagrams of the control circuit

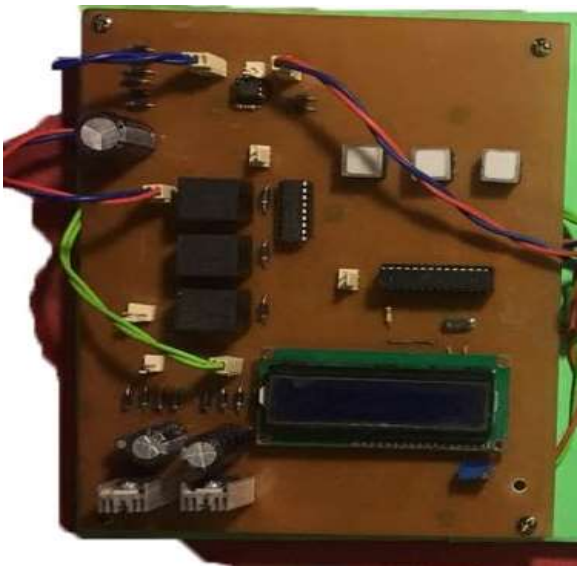

Fig. 5. The Hardware of Main Control Circuitry

VIII. CONCLUSION

In this research work and experimental setup, a novel mechanical storage system is implemented, its performance characteristics and working principles are fully analyzed. The satisfactory results were achieved upon implementing this PHCA setup.

This transitive model of PHCA storage system was deployed, tested and validated under different testing conditions, the

dynamic response of the system was obtained under varying set points of different parameters.
The response of power generation from the PHCA system was obtained under varying the pressure and water set points in the main PHCA energy storage tank. The whole PHCA system was run on different pressure set points and different volume of water/air combination stored in the tank

A. Results Achieved

The basic functionality of this system was confirmed and scale up analysis using prototype model setup showing the generation and storage of energy in efficient and reliable form responding to varying values of pressure and water stored in the tank.
Conversion/Efficiency assets of the PHCA system were determined for their impacts of long-term conservation and storage that they offered. The observed results were satisfying one depending upon chosen parameters. The efforts were successful in implementing this totally new idea and gave the desired results.
This innovative Generation and Storage system achieved several noteworthy results including the following:

- The PHCA storage system can be implemented on a simple structure, high efficiency and low cost compared to the other storage systems.
- The PHCA can store the energy in a bulk quantity with high efficiency.
- The storage of 60 Liters at 500 PSI pressure of Compressed Air in the PHCA storage tank produced the power of 120 Watts.
- The System operated at 12Volts and could run the load of 10 Ampere.

- The output power-time curve of the experimental PHCA system at the load of 100 watts at 12 volts for 8 minutes of operation is shown in Fig. 6.

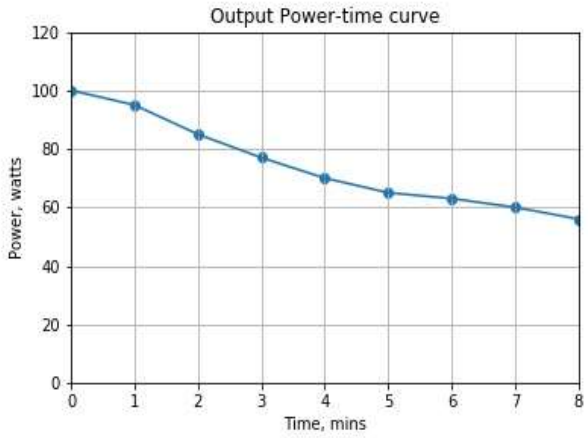

Fig. 6. Output Power-Time curve of Hydro Turbine

The performance of this system on a lower scale and obtained results confirm that this project can be installed for higher scales. The product can be installed at multiple generation and storage sites. For e.g. Large Process Industries which generate their own power and tends to store them for their future consumption. This system could provide its services at various mega industries. It could also be implemented in the national power system to increase its reliability by proper conservation of energy. The PHCA, besides being emission-free technology has the above operating advantages adding value to the electric system by increasing its efficiency, reliability and security.

B. Future Work

These preliminary findings warrant further developments in this novel generation, storage system, and its installations at large scales. The PHCA system has the capability of bringing many reform in the current development of power system. This paper presents the glimpse of the actual technology by presenting its working model. But, this system should be further studied from many aspects including mathematical modeling, control strategy, and energy management. The further improvements in this system will make it capable to be applied at various power generating stations, micro-grids, and smart grids.

ACKNOWLEDGMENT

First and foremost, we wish to thank Almighty Allah for giving us strength and courage to complete this research. We are thankful to “Innovation and Entrepreneurship center” (IEC), MUET, who provided us the funding under its project “Research Incubation in Public Sector Universities” (RINU) to develop this final year project.

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