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Design and analysis of the novel concept of high temperature heat and power storage

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ABSTRACT

A major portion of the electricity demand in Denmark is provided by wind farms. As wind power fluctuates sharply, there may be either surplus power or electricity deficit relative to the local demand. Thus, storing the surplus electricity and reclaiming it in demand times can increase the power plant incomes and reliability. On the other hand, as Denmark is one of the countries in which energy consumers are supplied by district heating, the demand for efficient and reliable heat production systems is also high. In this work, a novel and efficient energy storage system capable of providing both heat and electricity is designed and analyzed. This system is a smart combination of a thermal energy storage system and a gas turbine cycle without any combustion chamber. In order to have an optimal configuration, the system is designed based on thermodynamics criteria and net economic revenue. It is shown that the designed system may present an overall energy efficiency of about 90% and an electricity efficiency of approximately 35%. The economic assessment indicates that this innovative high temperature heat and power storage system, even taking into account conservative electricity and heat prices, is very profitable.

1. Introduction

Studies on the integration of renewable energy source systems are often conducted with a special focus on the electricity sector. During the recent years however, it has become clear that the least cost solutions for stabilizing the fluctuating power sources, such as wind and solar, is likely strong coupling between the different energy sectors. This concept is known as smart energy [1]. Conventional cogeneration system (CHP) is an example of such strong integration, coupling electricity and heating sectors. Traditionally, heat from CHP plants has been regarded as a byproduct of power generation, but in countries like Denmark in which the share of wind energy is approaching 50% of the electricity production, the business case of CHP is challenged and heat production is becoming the primary income stream. In this context, the storage solutions for balancing the fluctuations of heat and power production systems are becoming interesting.

1.1. Electricity storage

Battery storage is an efficient storage system for electrical energy. It emerged in the early 20th century and it is still widely used in the power production industry. Especially, in renewable energy source power plants [2]. Batteries are typically limited for their short term applications, their high cost and also due to some technical problems such as high energy dissipation rates etc. [3]. Thus, alternative energy storage systems have become of interest. In many of these systems, surplus electricity produced during low demand periods is stored in different forms and it is reclaimed later in peak period to balance the supply and the demand [4].

The first alternative electricity storage technology proposed after the battery was pumped hydroelectric storage, which was introduced in 1929 [5]. Today, this technology is very well established and commercially available from low capacities up to very large capacities as high as 4000 MW. The main advantage of this technology is the very long lifetime of the system and its high round-trip efficiency, i.e. 70–85%. The main drawbacks that restrict its application are the large capital investment, its dependence on topographical conditions and large land use [6,7]. Flywheel energy storage is another option that is available for applications ranging from 3 to 130 kW h [8]. Although this energy storage technology offers some important advantages such as low maintenance costs, long life cycles up to 20 years, no carbon emissions, very fast response and efficiencies in excess of 90%, it suffers from some deficiencies such as high rates of self-discharge of about 3–20% per

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hour, high capital cost and low storage capacity [9]. Compressed air energy storage (CAES) is another technology that has been found as an efficient energy storage system and extensive research has been devoted to this topic recently [10]. The CAES could be employed for capacities ranging from 50 to 300 MW [11]. The system is considered as an appropriate candidate for large scale applications because it can store energy for longer periods than most of the other methods, its efficiency is as high as 70% and it has a fast response. The CAES also has some disadvantages such as special geological site requirements, not fully developed technology etc. [12]. In addition to the aforementioned systems, there are several more energy storage systems, such as cryogenic energy storage and hydrogen base energy storage systems, each of which has its own advantages and disadvantages [13].

Even though some of the systems described above, especially the CAES and the pumped hydroelectric energy storage systems, can be employed for large scale applications with relatively high efficiencies, the existence of new, reliable, cheaper and more efficient energy storage systems is clearly perceived [14]. Investigations indicate that an optimum energy storage system should enhance the reliability of renewable energy sources, improve the resilience of the grid and realize the benefits of smart grids [15]. Also, in implementing an optimum storage project, one should take into account investigating the best type and size of the storage system in accordance with the application, defining its best control strategy and investigating the net present value (NPV) of the storage system [16].

1.2. Thermal storage

Thermal energy storage is a technology that reserves thermal energy by heating a medium. The stored energy may be reclaimed later for heating, cooling or power generation applications [17]. Generally, three different energy storage methodologies exist, namely, sensible heat storage (which is based on storing thermal energy by heating or cooling a liquid or solid storage medium [18]), latent heat storage (which is on the basis of phase change materials [19]) and thermo-chemical storage (which is based on chemical reactions [20]). Among these three different approaches, the sensible heat storage method is more practically used for both domestic and industrial applications as it is generally cheaper and more feasible than other two methods, though it may require large volumes due to its low energy density [21]. The most common types of storage mediums for the sensible thermal energy storage are water, soil, rocks, concrete or molten salts [22]. In designing suitable and efficient thermal energy storage system for a given application, some important factors must be taken into account such as the operation temperature range (over which the storage medium must operate), charging and discharging rates, heat losses from the storage (which must be kept as low as possible) and the capital and O&M costs [23]. In addition, the storage capacity, which has significant effect on the performance of the other components in the system, is an important factor. Overall, for short-term storage applications, the most economical capacity of the system is that by which the system meets fluctuations over a period of two or three days [24].

In this work, a novel, simple and efficient energy storage system for renewable energy source power plants such as wind farms, is proposed and designed. This system is show-cased for Denmark where district heating is as important as power generation, and as a result, a considerable portion of the stored energy in low demand times is used to support the local district heating system. In order to have a proper design, the local power production of one of the wind farms of Aarhus city in Denmark as well as its district heating system conditions have been taken into account as the case study of this work.

2. The novel energy storage system

In this section, a detailed operational description of the novel proposed energy storage system is presented. A similar design was recently proposed in a Danish technical blog by H. Stiesdal [25]. In this work, the configuration is modified considerably and the system is designed to achieve the maximum possible efficiency. The schematic of this system is presented in Fig. 1. The concept is centered around a large thermal storage system, which is initially charged once up to the high temperature of 600 °C. In the operational stage, the system may have a charging or a discharging process.

In the charging process, surplus power output of e.g. wind turbines is simply used for heating the thermal energy storage medium up to higher temperatures using electrical coils or similar. The capacity of the storage should be so selected that a maximum temperature of no higher than 950 K (about 680 °C) is reached over the year.

In the discharging step, i.e. in case of power deficit in the system, the energy storage starts working to offset electricity ramps. In this case, the system will take the following procedure for energy generation:

i) The multistage compressor set, and consequently the multistage turbine set coupled with that, is first driven by some prime-movers.
ii) The compressors intake ambient air to produce hot and compressed air. The hot-compressed air after each compression stage passes through the water heat exchangers to produce hot water for district heating use.
iii) The hot-compressed air after the last stage of compression passes through a heat exchanger supported by the hot airflow coming out of the thermal energy storage to be heated up to the highest possible temperature.
iv) The heated compressed air is then expanded through the multistage turbine set to produce rotational work. The airflow coming out of each turbine stage is heated up again through the heating heat exchangers to be more appropriate for the next stage of the expansion process.
v) The rotational work is converted to electricity by an electricity generator.

Considering the operational description given for the system so far, at first sight, it could be claimed that the general operational strategy of the system is based on the Bryton Cycle (gas turbine) and as it takes advantage of multiple stage turbines and compressors (isothermal processes instead of low efficiency adiabatic procedures) the system may look more like an Ericson Cycle. However, it should be noted that this system is, in fact, different from both of them as it employs a thermal energy storage system as its energy supply source. In addition, this system produces much amount of heat; as a result, the design is so that energy waste stands at its minimum level and the efficiency is as high as possible.

After presenting the system operation description, there are still some important points that should be taken into account. These points are addressed hereunder:

- The maximum temperature of 950 K is chosen due to the restriction in materials required for heat exchangers and expanders. In fact, the cost of heat exchangers increases significantly for the temperatures above this value as more resilient materials are required [26].
- The thermal energy storage system is a hot rock cavern with enough air space in between to allow air with a pressure slightly higher than ambient pressure to circulate in the system.