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Efficiency analysis and controller design of a continuous variable planetary transmission for a CAES wind energy system

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HIGHLIGHTS

- ▶ CAES wind energy system expands the operable range for wind generator system.
- ▶ The controller makes the windmill work at its optimal efficiency.
- ▶ The energy transforming process excludes electrical transforming process.

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ABSTRACT

This study proposes a CAES wind energy storage system composed of a windmill, a continuous variable planetary (CVP) transmission, a flywheel, a clutch, a reciprocating compressor, and an air tank. The mode of transformation of wind energy into compressed air in the system is also illustrated, in addition to details on the process of the controller design. The system controller can adjust the gear ratio according to the wind speed (V_{wind}) and rotational speed of the flywheel ($\omega_{flywheel}$). With a proper controller design to control the gear ratio, the flywheel can rapidly reach a rotational speed that is suitable for compressing the air into a tank. In addition, the windmill can be operated at the most efficient point. Therefore, transformation efficiency of wind energy into compressed air could be improved. After completion of the controller design, the efficiency of the two air compression systems (one system is driven directly by the windmill and another is driven by the flywheel) are compared to determining the target for improving performance in the future.

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1. Introduction

Wind power is currently a globally used renewable energy source. It provides an efficiency approach to generate energy without emitting carbon dioxide. Because the generator is driven by natural wind, the unstable character of wind would cause the energy generated by the wind turbine to fluctuate. Therefore, the generated energy must be stored and released with varying energy quantities. The most common approach to store electricity is by batteries, but batteries are expensive and environmentally unfriendly. Compressed air energy storage (CAES) was recently used as an energy storage method for wind power systems. According to the Electric Power Research Institute (EPRI) [1] statistic results, the total capital installed cost for storing wind energy by using CAES is approximately \$125 $kw^{-1}\,h^{-1}$ for 8 h storage duration, and is approximately \$450 $kw^{-1}\,h^{-1}$ for 4 h storage duration for the advanced lead acid storage. A review of CAES based on previous studies focusing on generated electricity shows that the CAES-coupled electricity system has great potential to supply a large proportion of electricity needs in the future [2]. To improve the efficiency of polytropic configuration of CAES, high-temperature thermal storages (>600 °C) and temperature-resistant material for compressors are essential [3]. The highest efficiency varies between 52% and 62% for two-stage compressed configuration with these thermal demands. CAES can also be coupled with diesel engines to improve system efficiency [4].

In the Iowa Stored Energy Park, wind energy generated at off-peak is also stored by CAES, and the compressed air is maintained in an underground cavern [5,6]. With the compressed air stored, electricity can be generated by the CAES turbine generator which is driven by the mixture of combusted natural gas and compressed air and has better performance than the conventional natural-gas combustion generator. The energy-transforming process of the park is described as follows: Electricity is generated by windmills and supplies according to electricity needs and the remaining electricity is used to compress the air. The energy stored by compressed air is released to the CAES turbine generator to generate electricity. There would be some losses of the total energy due to

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Nomenclature

V_{wind}	wind speed (m/s)
$\omega_{flywheel}$	rotational speed of the flywheel (RPM)
η_c	efficiency of transforming mechanical energy from the windmill into potential energy of the compressed air (%)
η_w	efficiency of transforming wind energy into the mechanical energy of the windmill (%)
η_{all}	efficiency of storing wind energy into the potential energy of compressed air (%)
W	energy stored in compressed air (J)
P	pressure of compressed air (N/m^2)
V	tank volume (m^3)
γ	polytropic exponent γ is equal to 1.4 at adiabatic process for standard air
E_i	energy captured from the wind of system B (J)
E_f	energy lost by the friction of system B (J)
E_p	energy system B actually obtains (J)

the transforming process in the park's operation, such as the energy is transformed to electricity by wind turbine first and then transformed to the internal energy of compressed air by a compressor later. Since the energy captured by windmill and the energy to drive compressor are both mechanical energy, therefore, there is no reason for a process to transform energy into electricity in between the capture and usage of mechanical energy. Maybe the mechanical energy captured by windmill can be used to compress the air without energy transforming process.

Windmills usually generate electricity with limited wind speed range. The wind turbine system we chose generates electricity when V_{wind} is larger than 4 m/s and stop when V_{wind} exceeds 15 m/s. The limitation of the useful wind speed is caused by the restriction of the electric generator. Nevertheless, there is no limitation of wind speed for using wind energy to compress the air. In other words, the operable range of wind speed to compress air is broader than for electricity generation.

Xiao et al. [7] propose a wind energy-catching system which is composed of a windmill, a compressor, pipes, and a tank. In this study, the windmill, which is connected directly to the compressor, drives the compressor by using rotational energy transformed from the wind energy. However, the system's operation cannot be adjusted because of the lack of a control unit. This means that the wind energy that is transformed into the rotational energy of the windmill may not reach its optimal efficiency.

This study proposes a CAES wind energy storage system composed of a windmill, a continuous variable planetary (CVP) transmission, a flywheel, a clutch, a reciprocating compressor, and an air tank that is also proposed and examined in the Shaw et al. [8]. The purpose of this research is to design a controller that can control the system by adjusting the gear ratio according to V_{wind} and the rotational speed of the flywheel ($\omega_{flywheel}$). With a proper controller design, the flywheel can rapidly reach the rotational speed that is suitable for compressing air into a tank. Furthermore, the windmill can be operated to its optimal efficiency by using this controller, thereby improving the efficiency for transforming wind energy into compressed air.

2. System configuration

To make efficiency comparison with the system we proposed, we will take the efficiency of our components into the idea of wind power-compressed air storage system. The system for comparison is called system A and its configuration is shown in Fig. 1a. System A is composed of a windmill, an air compressor, a high pressure storage tank and a fixed gear ratio without a controller.

The system we proposed is shown in Fig. 1b. The conceptual system arrangement consists of a windmill, a bevel gear, a continuously variable planetary transmission (CVP transmission), a controller, a flywheel energy storage system, a clutch, a reciprocating air compressor, and a tank. The function of each part is introduced as follows:

Windmill: the windmill captures the wind energy and transforms it into mechanical energy. This study adopts a vertical windmill because it can capture wind blowing from every direction.

Bevel gear: the bevel gear changes the rotating direction of the windmill shaft from vertical to horizontal. Chains and chain wheels are used to transmit the rotational energy from the windmill to the CVP.

CVP transmission [8]: the bevel gear of the windmill drives the flywheel through the CVP. The *NuVinci* CVP of Fallbrook Technologies was chosen for this research, and it is driven by a chain with a ratchet to prevent the flywheel energy from driving the windmill when the flywheel speed is higher than that of the windmill.

Controller: the CVP controller adjusts the gear ratio according to $\omega_{flywheel}$ and V_{wind} to ensure that both are operating under optimal efficiency conditions.

Flywheel energy storage system: the flywheel stores the wind energy captured by the windmill in the form of rotational energy. The flywheel is designed to drive the air compressor when it has enough rotational energy for air compression.

Clutch: the clutch connects the flywheel with the reciprocating compressor to achieve as many complete cycles as made available by the rotational energy of the flywheel for air compression.

Air compressor: the reciprocating air compressor transforms the rotational energy into the compressed air.

Tank: The tank stores the compressed air.

Most parts of the subsystem are modified from commercial product and the specification of these subsystems are shown in Table 1.

The operation process of system B is described as follows. First, the vertical windmill is used to capture the wind power from each direction. The wind energy is transformed into rotational energy through the windmill. Thereafter, the rotational energy of the windmill is transmitted to the flywheel and stores it through the bevel gear and the CVP. The rotational speed is increased when increasingly more energy flows through the flywheel. When the rotational speed reaches a certain speed, the compressor achieves several complete cycles of air compression by connecting the flywheel and the compressor with the clutch. The rotational energy in the flywheel is transformed into the compressed air stored in the tank. The whole process enables transformation of the natural wind energy into compressed air. When the wind is strong enough to have sufficient torque for driving the compressor, the clutch is activated throughout to drive the compressor continuously. However, when the wind is insufficient in strength, the clutch is

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