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Feasibility study of a hybrid wind turbine system – Integration with compressed air energy storage

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HIGHLIGHTS

- A new hybrid wind turbine system is proposed and feasibility study if conducted.
- A complete mathematical model is developed and implemented in a software environment.
- Multi-mode control strategy is investigated to ensure the system work smoothly and efficiently.
- A prototype for implementing the proposed mechanism is built and tested as proof of the concept.
- The proposed system is proved to be technically feasible with energy efficiency around 50%.

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ABSTRACT

Wind has been recognized as one of major realistic clean energy sources for power generation to meet the continuously increased energy demand and to achieve the carbon emission reduction targets. However, the utilisation of wind energy encounters an inevitable challenge resulting from the nature of wind intermittency. To address this, the paper presents the recent research work at Warwick on the feasibility study of a new hybrid system by integrating a wind turbine with compressed air energy storage. A mechanical transmission mechanism is designed and implemented for power integration within the hybrid system. A scroll expander is adopted to serve as an "air-machinery energy converter", which can transmit additional driving power generalized from the stored compressed air to the turbine shaft for smoothing the wind power fluctuation. A mathematical model for the complete hybrid process is developed and the control strategy is investigated for corresponding cooperative operations. A prototype test rig for implementing the proposed mechanism is built for proof of the concept. From the simulated and experimental studies, the energy conversion efficiency analysis is conducted while the system experiences different operation conditions and modes. It is proved that the proposed hybrid wind turbine system is feasible technically.

1. Introduction

In recent years, wind power generation has shown a robust growth trend worldwide. The global cumulatively installed generation capacity of wind power reached 318,137 MW at the end of 2013, which has increased by more than 163% compared to 120,624 MW in 2008 [1]. Such rapid development is mainly driven by the continuous increase in electricity demand and the need for reducing greenhouse gas emissions. However, the nature of fluctuation and intermittence of wind makes it very difficult to deliver power output from wind energy with an instant match to the electricity demand. This nature also brings the negative impact onto the wind turbine system operation efficiency, life expectance and mechanical structures [2]. Thus, new technologies and approaches have been actively researched to alleviate the problems caused by wind fluctuation and intermittence, such as wind turbine pitch angle control, power electronics development for wind power and flexible back-up power generation [3–5]. One of the promising solutions is to introduce an element of stored energy as an alternative energy supply for use when the ambient wind power is insufficient. Various Energy Storage (ES) technologies can provide the service of compensators to work with different types of wind power generation systems, for example, hydroelectric pumped storage, Compressed Air Energy Storage (CAES), flow batteries

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and flywheels [6,7]. Among the available ES technologies, CAES can be considered as one of the relatively mature and affordable options [6,8,10].

CAES technology refers to storing energy in the form of high pressure compressed air during the periods of low electrical energy demand and then releasing the stored energy during the high demand periods. CAES facilities exist in multiple scales, with long storage duration, moderate response time and good part-load performance [6,7,9]. So far, there are a few successful industrial implementations of large-scale CAES plants serving wind power generation. For instance, after the world first commercialized Huntorf CAES plant started operation, its mandate was updated to include the buffering against the intermittence of wind energy production in Northern Germany [9]. Also, the developing advanced adiabatic CAES demonstration project – ADELE by RWE Power and others aims to store large amounts of electrical energy through CAES and thermal storage concepts; ADELE plans to operate with a wind farm, with a storage capacity of 360 MW h and no CO_2 emissions in a full cycle [11,12].

In addition to the large-scale CAES facility integrated with the wind power generation, the work presented in the paper is to explore the potential of using small scale CAES in the wind power application. Inspirited by the parallel drive train in Hybrid Electrical Vehicles (HEVs) ([13]), this paper presents a novel direct electromechanical integration of a wind turbine system and a CAES mechanism at a few kW s scale. The objective is to develop a system with simple structure, efficient, low maintenance, clean and sustainable. The proposed design is illustrated in Fig. 1. It consists of three main sections:

(1) Wind turbine subsystem: this subsystem simulates a real scenario of horizontal wind turbines' operation. It includes a module of wind power extracted by blades, a mechanical drive train, a Permanent Magnet Synchronous Generator (PMSG) and its load(s) to be driven. The generated electricity can be directly used to end-users or fed back to grids via electric power converters and inverters.
(2) CAES subsystem: it is composed of a scroll expander and a compressed air storage tank. This relatively new type of expander has a smart mechanical structure leading to a higher energy conversion ability compared to most other pneumatic actuators. Due to the capacity of typical scroll expanders, the proposed structure is suitable for small-scale wind turbine systems. The compressed air stored in the storage tank can be obtained from the operation of compressors on site or local suppliers. From Fig. 1, through a mechanical transmission mechanism, an additional driving power by the CAES subsystem can provide a direct compensation to the wind turbine.
(3) Controller: for managing the whole hybrid system's operation, investigating an appropriate control strategy is particularly important for supporting the system multi-mode operations and ensuring the dynamic balance of driving power and electric load demand.

Study of hybridization of wind generation with CAES was reported in various literatures, for example, [14–17]. The common feature of the previously reported hybridization systems is that CAES is treated as an independent energy storage unit and is engaged with wind power generation through management of electricity network connection. The hybrid system proposed in this paper is mainly new and different because the CAES is directly connected to the turbine shaft through a mechanical transmission mechanism. In this way, with a proper control strategy, the compressed air energy will be released via the direct mechanical connection to contribute to wind turbine power generation. Thus the system does not require a separate generator and extra electricity conversion device(s) which will reduce the whole system cost. In addition, the extra torque input from the air expander could reduce the turbine shaft stress for prolonging the turbine life time.

The paper starts from description of the hybrid system, development of its mathematical model, and presentation of a suitable multi-mode control strategy. Then a hybrid wind turbine test rig is reported, which is installed in the authors' research laboratory. Finally the whole system energy conversion efficiency analysis is given.

2. Mathematical model of the hybrid wind turbine system

In this subsection, the mathematical models for a typical wind turbine, a Permanent Magnet Synchronous Generator (PMSG), a scroll expander and a novel mechanical power transmission system are presented, and then the whole system control strategy is described. In the modelling study, it is assumed that the air supply of the scroll expander, i.e., the compressed air from the storage tank, is sufficiently pre-compressed air with constant temperature. Thus the scroll expander air supply can be regarded as a controllable compressed air source.

2.1. Mathematical model for wind turbines

A typical horizontal axis wind turbine is chosen in the hybrid system for modelling study. Its mechanical power output P which can be produced by the turbine at the steady state is given by:

$$P = \frac{1}{2}\rho_a \pi r_T^2 v_w^3 C_p \tag{1}$$

where ρ_a is the air density; r_T is the blade radius; v_w is the wind speed; C_p represents the turbine efficiency, revealing the capability

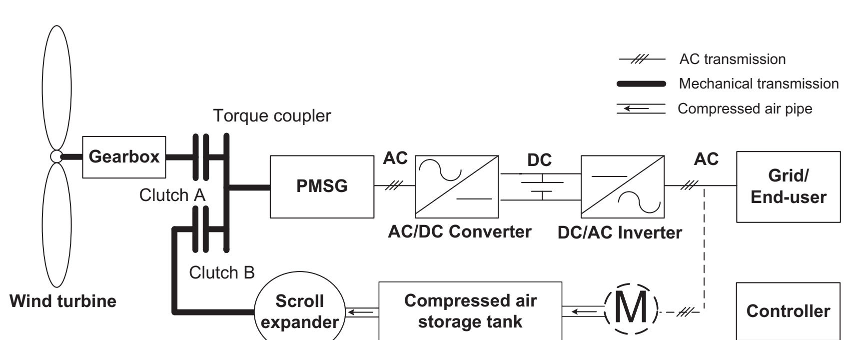

Fig. 1. Small-scale hybrid wind turbine with CAES.