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Improving power grid performance using parallel connected Compressed Air Energy Storage and wind turbine system

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A B S T R A C T

Wind energy is boundless renewable energy which can be tapped continuously. It is clean and free energy in comparison with conventional fossil fuels. However, the high stochastic nature of the wind could affect the power quality of a grid system fed from a wind turbine system. Compressed Air Energy Storage (CAES) is a mature energy storage technology for handling wind fluctuation problems such that the generated energy could be supplied to the grid without affecting grid performance. This paper proposes a parallel connection of the CAES with a wind turbine to provide a continuous supply to the grid system with reduced wind power input fluctuations. Analysis was carried out using MATLAB Simulink to study the effectiveness of the parallel CAES system with changes in wind speed. The results were focussed on the grid's voltage and active power. The results showed that the proposed parallel CAES system was able to smooth out wind power fluctuations and able to provide continuous power supply to the grid system with lower power consumption during the CAES compression process when compared to the series CAES system.

1. Introduction

Wind power has shown tremendous growth in capacity globally between the years 1996 until 2012 [1]. The European Wind Energy Association's expects wind energy to provide up to 15.7% of Europe's 230 GW electricity demand by 2020 and 28.5% of 400 GW demand by 2030. It is also expected that the generated wind energy in 2050 can provide half of Europe's power [2]. The production of electricity using wind energy can save several billion barrels of oil and avoid carbon emission and various types of greenhouse gasses. However, the main drawback of wind energy is its stochastic attribute which depends on spatial and temporal resolution. It can only operate after a certain cut-in speed is reached and will stop operation if the wind speed exceeds the cut-out speed in order to protect the wind turbine system.

Several common approaches have been introduced in dealing with these fluctuation problems such as adjusting the pitch angle and rotation speed of the wind power generator, transferring generated wind power through DC link and inverter control system and applying energy storage, as reviewed in the literature [3]. Nonetheless, this paper looked into the effectiveness of Compressed Air Energy Storage (CAES) system to effectively suppress the fluctuations of energy supply from a wind turbine.

In comparison with other energy storages like, battery energy storage, flywheels energy storage and supermagnetic energy storage, the installation cost of CAES is reported to be much cheaper by approximately half of the costs of lead-acid batteries [4]. Furthermore, in order to create a workable and sustainable mitigation system in wind power fluctuation, the energy storage system should have long life cycle to charge and discharge more frequently, have high power density to handle the transfer rates and high energy density to store abundant energy [5]. These attributes were also reported in Ref. [6]. Studies have also shown that an energy storage system with proper control systems will be able to absorb small variations in wind power output and reduces negative impacts on existing power grids [7,8].

Compressed Air Energy Storage is a relatively mature energy

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storage which stored energy in the form of compressed air. There is growing number of research works which covers both technical and economic aspects had been published [9–11]. Detail analysis and overview of the past, present, and growth of CAES systems are clearly described in Ref. [11]. Charging and discharging process of CAES plays an important role in explaining its economic analysis. These were studied in Ref. [12] using three independent computer-based methodologies to identify the optimal operation strategy for a given CAES plant, spot market and the year in operation. These methods are based on detecting the trigger point to buy or sell the electricity at the best business-economic net earnings of CAES. In terms of its application in wind power system, CAES proves to be able to tackle spinning reserve, load following, peak shaving, time shifting, fluctuation suppression and transmission curtailment problems [6,13–15].

Generally, CAES system could be integrated with a wind turbine system in a series or a parallel system as shown in Fig. 1. In parallel wind-CAES system the air compressor and the expansion turbine are on the same shaft as the wind turbine, whereas in series CAES the compressor is powered by the wind turbine, without any direct mechanical connection to the expansion turbine. In both cases the compressed air is stored in tanks (in salt cavern/tank as in Refs. [11,16]) and later on, during high peak demand, the stored compressed air is expanded through a turbine to obtain mechanical power to run the generator to obtain electricity.

Basbous et al. [4] proposed a combination of CAES with wind diesel to reduce fuel consumption, operational cost and pollution. Thus, instead of combining other energy storages system with CAES to mitigate wind fluctuation, this paper proposed a parallel connection of wind CAES system. The parallel system helps to further reduce the power consumption during compression process, compared to a series system.

This paper also gives detail derivations of the mass flow rates of air leaving the tank in single stage expansion process application. The results were analyzed based on parameters involved during air compression as well as voltage and power delivered to the grid system.

2. Wind and Compressed Air Energy Storage modelling

The energy in the wind is transformed into shaft mechanical energy by a wind turbine. An electrical generator such as the permanent magnet synchronous generator (PMSG) then transforms the mechanical energy into electrical energy. In this study, a wind turbine with a rated wind speed of 12 m/s was used. If the wind speed is more than 12 m/s, the mechanical power runs the PMSG and the compressors to compress air into the tank. If the wind speed is less than 12 m/s, the compression train is set to idle (no compression process occurs) and the mass flow rate of air (*mfr*) entering the expansion train is only from the storage tank. The compression and the expansion trains are explained in detail in Section 2.2 and 2.3 below.

In this paper, this configuration is named as the parallel CAES. This configuration is a modified form of the existing series CAES. The series CAES is modelled such that the storage is charged during low electricity cost and discharged during high electricity cost [16]. These two CAES configurations are then compared to evaluate the capability of the parallel CAES to continuously supply mechanical power to the generator.

There are three main parts in modelling a wind CAES (series and parallel) system, namely the compression stage, tank storage and expansion stage. The first part focused on compressing atmospheric air and extracting the heat produced during the compression process. The second part is focused on air storage and the last

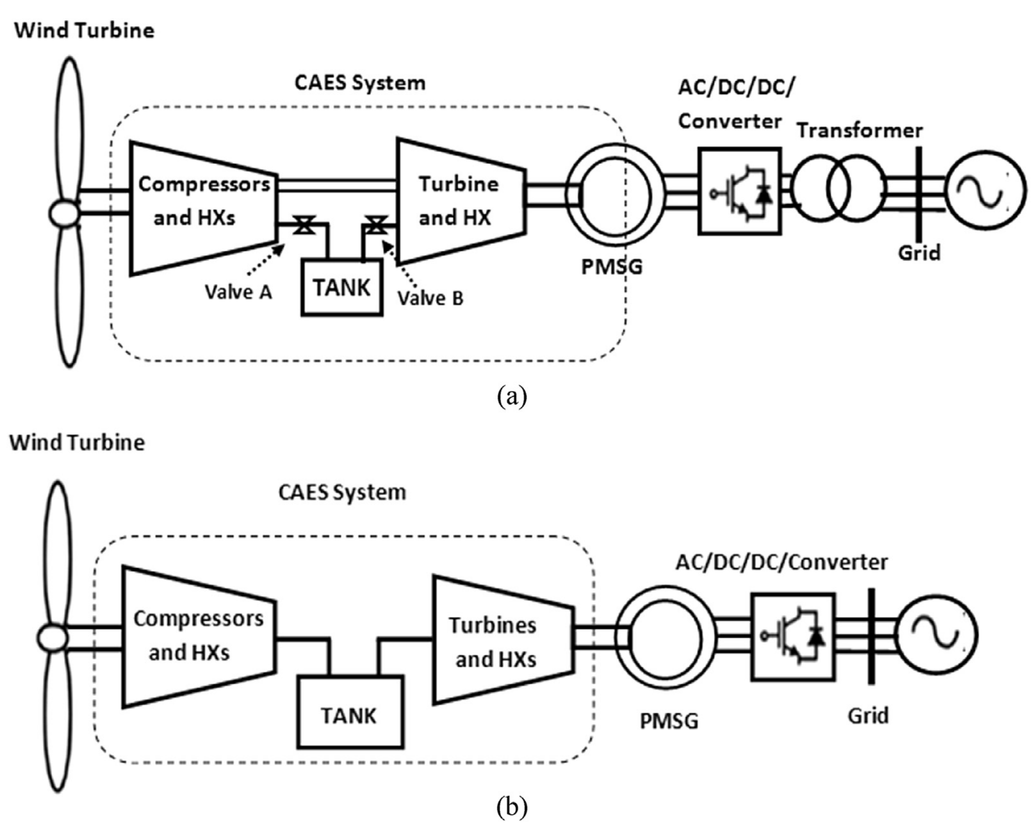

Fig. 1. Schematic diagram of (a) parallel connected Wind-CAES system, (b) Series connected wind-CAES system.