Renewable Energy 99 (2016) 69–79

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Hydraulic-electric hybrid wind turbines: Tower mass saving and energy storage capacity

Chao Qin*, Elijah Innes-Wimsatt, Eric Loth

Department of Mechanical and Aerospace Engineering, University of Virginia, 122 Engineer's Way, Charlottesville, VA, 22904, United States

A R T I C L E I N F O

Article history:
Received 13 July 2015
Received in revised form
1 February 2016
Accepted 14 June 2016

Keywords:
Wind turbine tower
Hydraulic drive
Energy storage
Cost reduction

A B S T R A C T

This study investigates concept of introduction of a hydraulic motor in the nacelle to convert rotor shaft work into hydraulic power that is transmitted to the electric generator at ground/sea level. This combination of hydraulic and electric power generation can help simplify or even eliminate the gearbox, and significantly reduce the head weight mass that the tower needs to support. Also, this hybrid concept allows energy storage in the tower which can reduce electric generator size. The analytical technique for tower mass savings employed herein was validated and used to show that 33%–50% of the tower mass may be saved through decreased tower thickness. In addition, the hydraulic-electric generator concept is compatible with employing isothermal CAES in the tower. Analysis based on cross-over pressure for the design limit indicates that this energy storage concept provides more than 24 h of energy storage if one considers S-glass towers of 10 MW or more. To accompany the above engineering analysis, a CAPEX cost model was developed based on recent production wind turbines and system designs. The hydraulic-electric hybrid system with CAES was estimated to yield a total CAPEX savings of 17% due to a substantial decrease in generator and electrical infrastructure costs.

1. Introduction

Wind turbine sizes have been steadily increasing over the last few decades due to advances in system design and component technology. The next generation of wind turbines (to be installed in 2020 and beyond) are likely to include extreme–scale systems (10 MW or more) for which the larger rotors have the potential to capture more energy per swept area due to higher wind speeds available at higher altitudes [1]. For extreme–scale systems, off-shore wind turbines hold promise of being an important source of energy due to a number of advantages [2–4]. First, off-shore sitting allows higher average wind speeds (which typically increase when distance from the shore goes further) which can increase energy capture for a giver turbine size. However, off-shore locations must include expensive marine support structures and undersea electric transmission wires with coastal substations. In addition, variable weather conditions result in increased time for transportation and installation that add to overall capital costs. Furthermore, there are challenges with integrating off-shore wind farms into electrical grids because of the distance involved. Since it is problematic to co-locate off-shore gas turbines to provide offset power during periods of low wind, the power coming to the shore will generally be highly unsteady. Therefore, the substations and transmission lines over this distance generally must be all rated by the peak power (and not the average power). As a result, the cost of energy for off-shore wind energy is generally significantly higher than many conventional energy sources and on-shore wind energy.

To reduce the cost of energy for extreme-scale wind turbines, especially those off-shore ones, a modification of the power generation is proposed as shown in Fig. 1. In the conventional concept (Fig. 1a), the rotor shaft is converted to electrical power using an electrical generator. A gearbox is generally used to convert the low-speed rotor rpm to the higher rpm required for the electric generator to operate most efficiently. For extreme-scale systems, the rotor rpm is reduced even further because of increased blade radius combined with a limit on blade tip speed (ca. 80–100 m/s). The increased gear ratio may require multiple gearbox stages that increase complexity and probability of failure [1,2]. As such newer turbines generally eliminate the gearbox by replacing them with direct-drive Permanent Magnet Generator (PMG), which are more expensive and heavier [5].

In the proposed hybrid power generator approach, shown in

* Corresponding author.
E-mail addresses: chaoqin@virginia.edu (C. Qin), ewi9ff@virgininia.edu (E. Innes-Wimsatt), loth@virginia.edu (E. Loth).

http://dx.doi.org/10.1016/j.renene.2016.06.037
0960-1481/

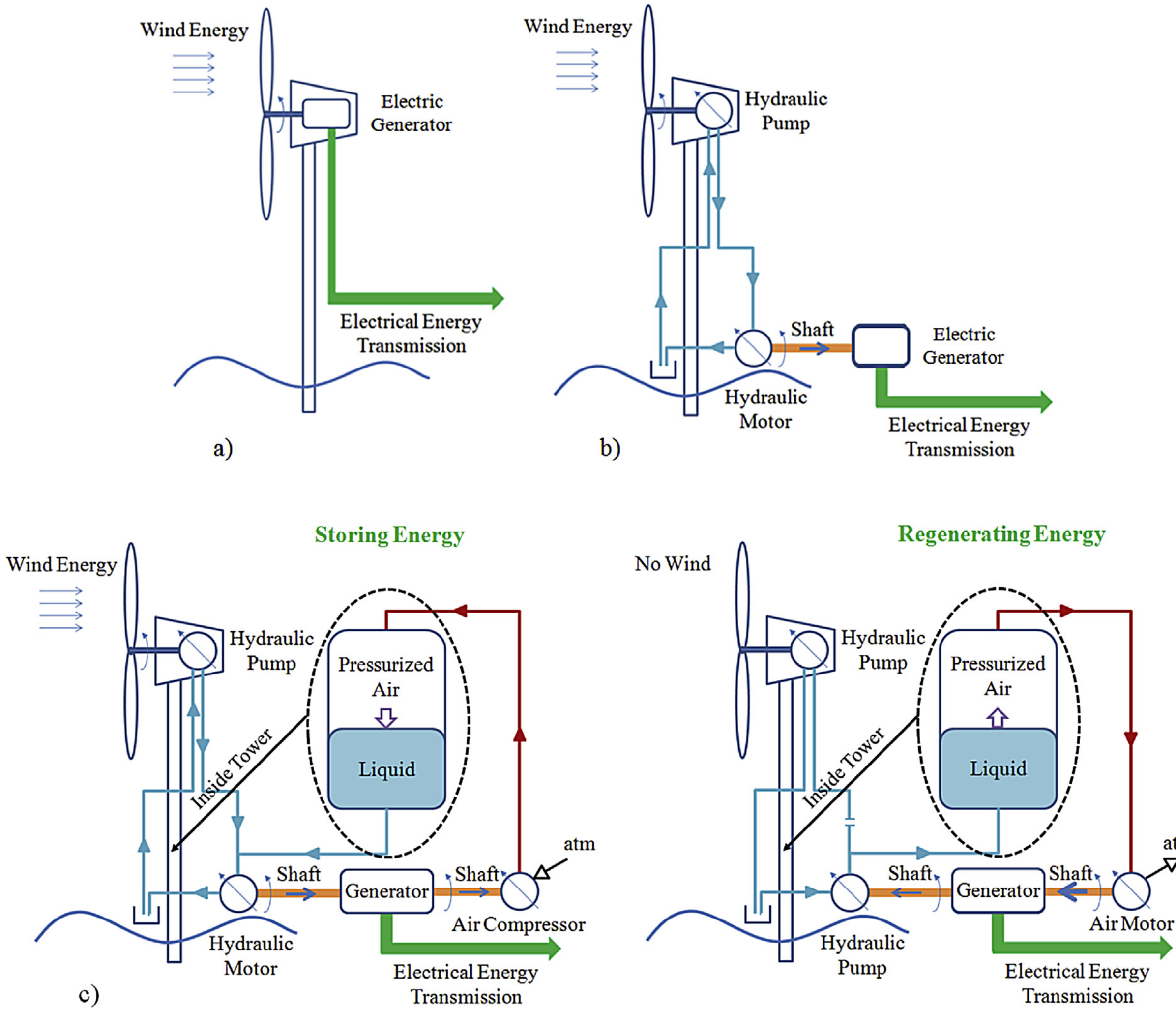

Fig. 1. Sketch of off-shore wind turbine system: a) conventional with electrical generator in nacelle on top. b) hydraulic-electric with electrical generator at base, and c) hydraulic-electric generator system with energy storage in tower.

Fig. 1b, the electric generator is moved down to ground/sea level so that the shaft work from the rotor is instead fed into a hydraulic pump in the nacelle linked to a hydraulic motor at the tower base which can driven the electric generator. Hydraulic transmission systems are normally used as continuously variable transmissions [35], and hence this modification reduces the mass and complexity of the nacelle drive components, and can eliminate the necessity of a gearbox or a PMG direct-drive system [6]. Use of a hydraulic pump and motor is preferred to that of a pneumatic pump and motor as the former has a much high power density. Also, the electric generator can be located at ground/sea level for ease of maintenance and can be driven at a high uniform rpm to help eliminate the complexity and cost of gearbox or PMG components. Perhaps most importantly, the relocation of the electric generator allows the tower head weight to be substantially reduced, allowing the structural mass of the tower and its foundations to also be reduced.

In a modified configuration, the above hybrid hydraulic-electric generator concept can also facilitate the use of an energy storage system in the tower volume as shown in Fig. 1c. During storage times (when wind power generation is too high), wind energy is transferred to shaft work by hydraulic pump and motor. Part of the work is used to generate electricity to satisfy the user's demand while the surplus work is stored in the open accumulator (inside the tower) through air compression. During regeneration times (when wind power generation is too low), compressed air is allowed to exit the open accumulator and expand near-isothermally to provide power through an air motor that drives the generator to produce electricity. In general, the energy storage and regeneration depend on profile of user's demand and real-time electricity price. Wind energy is stored when it goes higher than the demand, and the stored energy is regenerated and sold at high electricity price when electricity demand is increasing. Storage in the tower becomes more practical as the turbine size increases.

In particular, an isothermal Compressed Air Energy Storage (CAES) system as described in Refs. [7,8] is relatively compact (high energy per unit volume) and is highly compatible with such a hybrid generator. A multi-stage isothermal CAES can allow very high efficiencies, as much 89%, much higher than the conventional adiabatic CAES efficiencies of about 55%. Energy storage can level power input to the electrical generator, i.e. reduce the variation of incoming power so that fluctuations about the mean power are reduced. Since the conventional turbines often produce a peak (rated) power that is two to three time the average power, such leveling allows the generator size to be reduced. For example, a wind turbine with a 5 MW rating (a 5 MW generator in the nacelle) will have an average power of about 1.8 MW. If enough storage is