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Power conversion system for high altitude wind power generation with medium voltage AC transmission

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ABSTRACT

High Altitude Wind Power (HAWP) generating system provides clean energy at low cost and high capacity factor due to reduced size of the turbine and high speed streamlined wind at high altitude. An airborne wind turbine (AWT) at high altitude extracts kinetic energy from wind using buoyancy provided by the blimp/aerostat. The generated electrical power is then transmitted to the ground based station (without any power conditioning) using the transmission lines (tether). The power conversion system (PCS) for harnessing HAWP is proposed in this paper. The proposed PCS consists of a three-level neutral point clamped (NPC) rectifier, a three-level NPC DC–DC converter followed by a two-level inverter. Modelling, design and control of the PCS are presented and discussed. The PCS provides generation side maximum power-point tracking (MPPT) using sensorless optimal torque control technique. The DC–DC converter provides electrical isolation as well as voltage step-down functions. A modified proportional resonant (PR) control which can selectively eliminate lower order current harmonics of the grid-connected inverter is also presented. The proposed control scheme of the PCS is evaluated through simulation studies using software programs like PSIM and MATLAB. A scaled-down 1 kW laboratory prototype of the complete PCS is designed, built and tested. The experimental test results obtained validate the proposed control scheme for efficient power generation from high altitude wind and interface to the grid/load.

1. Introduction

The consumption of fossil fuel based electrical power generation system has adverse effects on the environment due to excess CO_2 emission. Solar power and wind power are the major sources of renewable energy that can be used to reduce the consumption of fossil fuel for electrical power generation [1], [2]. Over the past two decades, the wind turbine diameter has increased from 10 m to 125 m in order to increase power generation from 25 kW to 10 MW [2–5]. The increase in the turbine radius increases constructional cost of the conventional wind power generating system. Higher capital investment for the renewable energy sources has hindered the growth of renewable based power generating system.

Electrical power generated by the wind turbine is a function of turbine swept area, A_T and wind velocity, $\upsilon(h)$ as indicated in eqn. (1). With increase in altitude from the earth's surface, the velocity of wind increases as expressed by eqn. (2). So, at high altitudes above the earth's surface, a relatively small size wind turbine can extract large amount of electrical power.

$$P_{Tur} = \frac{1}{2}\rho C_P(\lambda) A_T \upsilon(h)^3 \tag{1}$$

$$\upsilon(h) = \upsilon_0 \left[\frac{h}{h_0}\right]^{\alpha} \tag{2}$$

where P_{Tur} is the electrical power generated by the wind turbine in Refs. *Watts*, A_T is swept area of rotor blade in Refs. m^2, υ_0 is the known wind velocity in Ref. m/s at the earth surface, $\upsilon(h)$ is the wind speed in Ref. m/s at an altitude h in m above the earth's surface, υ_0 is the known wind speed in Ref. m/s at a known altitude h_0 in m above the earth's surface, $C_P(\lambda)$ is the coefficient of power extraction by the turbine, and α is the Hellman's coefficient of the surface that depends on the terrain.

A 13 m rotor (radius) is required to generate 100 kW of power for the CWP generating system at 50 m altitude. However, a 3.1 m

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turbine radius based AWT is sufficient to generate 100 kW power at 1 km altitude above the earth's surface. The reduction in rotor radius decreases the infrastructure cost significantly. Therefore, HAWP generating system can be a cheaper source of clean energy in the near future. As the power rating of the system increases, the size of the blimp increases. For a 100 kW system, the estimated volume of the blimp is 400 m^3. At higher power rating, the required size of the blimp for buoyancy becomes large and is difficult to construct and operate. On the other hand, complex control methods are required to govern the position of AWT at very high altitude. Further, the floating unit at very high altitude may interfere with the aviation routes. Therefore, our research is focused on the design and development of a portable HAWP generating system rated upto 100 kW power at a maximum altitude of 1 km above the earth's surface. A thorough comparison of the CWP and the proposed HAWP is explained in Ref. [4].

The concept of harnessing HAWP using air-borne wind turbine-cum-electric generator is explained in Refs. [5], [7]. A light gas filled blimp/aerostat is used to provide buoyancy for a floating turbine in the sky. This generating system provides power for an isolated grid and as a source of portable power supply during emergencies and disaster situations. An animated prototype of a portable HAWP generating system developed by Altaeros Energy is shown in Fig 1 [6]. The conventional architecture of the complete electrical system for the blimp based HAWP generating system is explained in Refs. [2], [5]. The architecture consists of a permanent magnet synchronous generator (PMSG), a front-end rectifier, and a DC–DC converter in an air-borne unit and a grid connected power electronic converter (PEC) at the ground based station. High altitude wind turbine generates electrical power at three phase low voltage AC (LV-AC). The generated power is transformed into optimal medium voltage DC (MV-DC) for efficient transmission. This convectional method uses bulky air-borne PECs that increase the overall weight of the air-borne unit.

Recent studies have proposed a new electrical power architecture consisting of three phase medium voltage AC (MV-AC) power generation that matches with the optimal transmission voltage [7]. The proposed configuration eliminates the need for an air-borne PEC and therefore simplifies electrical power architecture enhancing the power-to-weight (P/W) ratio of the overall electrical system by 7% [7]. The increase in the generation voltage of the PMSG to match the optimal transmission voltage increases the weight of the generator by 20–25%. However, the P/W ratio of overall electric system increases due to the omission of the bulky air-borne PECs and reduction in weight of the transmission line. The detailed comparison between the conventional MV-DC transmission based system and the proposed new MV-AC transmission based system is presented in Ref. [7]. The electrical architecture based on MV-AC generation/transmission is illustrated in Fig 2. The complete electrical architecture consists of the PMSG and transmission lines (tether) in the air-borne unit and a PCS in the ground based station. The optimal generation/transmission voltages obtained for three different power levels are listed in Table 1 [7].

Fig. 1. A prototype of blimp based HAWP generating system developed by Altaeros Energy.

The proposed electrical system harvests variable voltage and variable frequency electrical power due to the variation in the wind speed. The transmitted electrical power needs to be fed into the distribution grid/isolated grid/isolated load at three phase 415 V and 50 Hz AC supply. Therefore, the PCS required for HAWP generation system should step down variable voltage and variable frequency AC power and feed into the grid at constant voltage and line frequency.

In Refs. [8–14], various power electronic converter topologies for the PMSG based wind farm/grid interface are described. These power converters do not provide electrical isolation and can not step down the DC voltage level significantly. The PCS for wind power harvesting system interfaces with a three phase diode bridge rectifier at generation side that does not have control on the generation side currents as explained in Refs. [8–10]. The PMSG based wind farm based on back-to-back converters for grid connection are designed and modelled in Refs. [11–14]. The power conversion system mentioned in Refs. [11–13] consists of rectifier-inverter connected in back-to-back configuration without electrical isolation. Indirect matrix converter (IMC) for three phase AC–AC conversion with high frequency AC link are studied in Refs. [13], [15–18]. The matrix converter with high frequency link eliminates the bulky DC link capacitors but the design and control of the matrix converter that requires intermediate battery storage interface is complex. Two stage matrix converter requires many devices and thereby increasing the semiconductor losses. In addition, matrix converters do not have unconstrained reactive power compensation, require complex feedback control of input and output currents, and demand high semiconductor chip area [18]. The complete design and control of PCS for MV-AC transmission based HAWP generating system has not been thoroughly investigated yet in the literature.

In this paper, a suitable PCS for HAWP generating system is proposed and compared with the conventional PCS. The control of the air-borne wind turbine for MPPT extraction is carried using optimal vector control method from the ground based station. The control of AWT is carried out using ground based NPC rectifier. In addition, the output voltage balance of the rectifier is also incorporated in the proposed control strategy. The effects of transmission line parameters on power conversion mechanism are studied and presented in this paper. The design of the intermediate DC–DC converter for providing isolation and step-down operation is also described. Finally, a two level inverter with L-C-L filter is designed, implemented, and controlled to interface the DC power into the grid using active power control. The two level inverter is controlled using a modified proportional resonant control which can selectively eliminates lower order current harmonics from the grid side current.

In Section II, discussions on the conventional and the proposed PCSs are presented. A comparative study of the PCSs and selection of a suitable PCS is described in Section III. Modelling and control of the selected PCS are carried out in Section IV. In order to include the effects of transmission line, lumped model of the cable is presented.