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Analysis on lightning triggering possibility along transmission tethers of high altitude wind energy exploitation system

Yiming Ji*, Jinliang He

State Key Lab of Power System, Dept. of Electrical Engineering, Tsinghua University, Beijing 100084, China

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ABSTRACT

Recently a new concept of umbrella–ladder combination system to exploit the high altitude wind energy has been proposed. In this system the polyethylene polymer transmission tether plays an important role as the connection between the high altitude wind power absorber and the ground station. To make the concept practical, whether the tether would lead lightning to the ground station is one of the key issues. In this paper, the possibility of the polyethylene polymer transmission tether triggering lightning is studied. Firstly, the lightning environment characteristics are summarized, especially the possible potential distribution and electric field distribution. The charge structure of the thundercloud and the lightning activities which may affect the high altitude wind energy absorber are described. Secondly, the ways of the tether triggering lightning under thunderstorm in static electric field produced by charge accumulated in thundercloud and in impulsive electric field produced by lightning are analyzed. The lightning impulse characteristic of the tether and the influence factors on it are obtained through experiment and the result shows that the critical lightning impulsive breakdown electric field is about 300 kV/m. Therefore there is a great possibility that the tether triggering lightning. Finally the simple lightning protection for the system is discussed.

1. Introduction

Generally, power generated by wind turbines increases by the cube of the wind speed. As shown by Archer and Caldeira [1], the jet stream wind speed at high altitude can be guaranteed steady and several times higher than that near earth surface. Hence the jet stream wind can offer energy one or two orders of magnitude greater than equal-rotor-area, ground-mounted wind turbines operating in the lowest regions of the Earth's boundary layer. O'Doherty and Roberts [2] have stated that the average power density is around 17 kW/m^2, and Cristina Archer states that tremendous energy which can be captured from high altitude winds is far more enough to supply the world's energy needs very economically. Furthermore, this high altitude wind resource is invariably available in northern India, China, Japan and elsewhere. It is these facts that lead many researches to propose various concepts for extracting electricity from high altitude.

The idea of electricity generation from high altitude winds can be dated back to 1930s. The company Sheldahl, Inc., placed a generator on a tethered balloon and generated power in the late 1960s [3]. Riegler and Riedler [4] proposed the idea of using a turbine wind generator mounted on a tethered aerostat. Then designs were presented to make the aerostats generate lift efficiently and to achieve the wind turbine better performance. Roberts and Shepard [5] described a concept of a rotorcraft which is situated near-permanently at high altitude. This main design is an airframe with two or more rotors which generate electricity as well as providing lift to support the airframe. The airframe is tethered by an aluminum–fiber composite which conducts the electricity to a ground station. Despite these concepts of attempting to locate an electric generator at high altitude, Ockels [6] proposed an alternative concept where power is generated by a series of high-lifting wings or kites that move cables through an electric generator. The concept was modified and developed gradually and became the so-called “Laddermill”. Bolonkin [7] proposed a system based on Laddermill with a high altitude rotor deployed below a stabilized body. Loyd [8] suggested kites could be used to either pull a load or lift a wind turbine on itself. Payne and McCutchen [9] proposed different ideas of tethered “self-erecting” structure to generate power from high altitude.

Most of the aforementioned concepts for extracting energy from high altitude winds utilize lifting bodies, whether balloons, aerostats, crafts, wings or kites, to work both as energy collector and balancer. The fact brings the problem of achieving the balance between generating power and body-balance.

Recently, the company, China Guangdong High Altitude Wind Energy Technology Co., Ltd. has proposed a new concept of

* Corresponding author at: Department of Electrical Engineering, Tsinghua University, Beijing 100084, China. Tel.: +86 10 62788811; fax: +86 10 62784709.
E-mail address: jiyiming44@126.com (Y. Ji).

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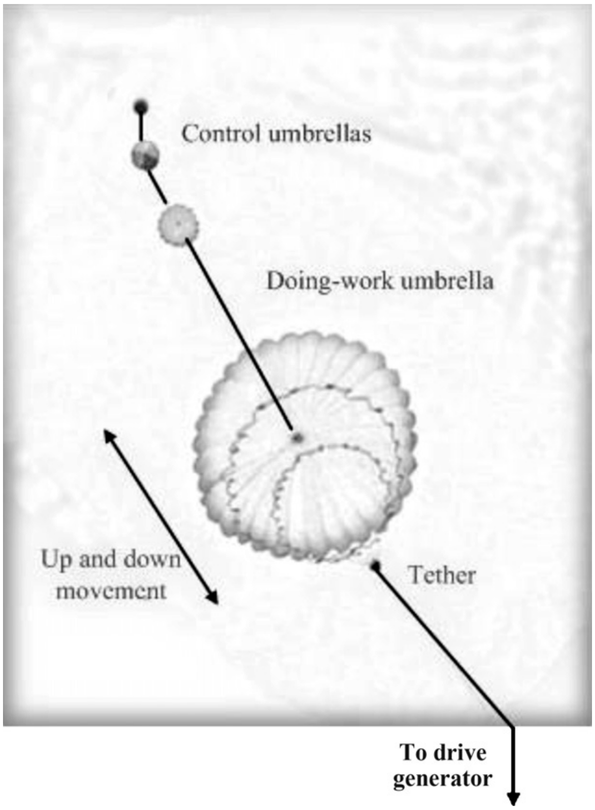

Fig. 1. The structure and working principle of the umbrella–ladder combination system.

extracting high altitude wind energy, which is called umbrella–ladder combination system [11]. The lifting bodies used in this system are umbrellas. The major improvement of the design is that the system consists of two parts: a working system and a balance system. The working system is composed of a series of tethered doing-work umbrellas and the upper balance system is composed of a series of tethered control umbrellas. Wind lifts the doing-work umbrellas and drives the ground generator mechanically through the tethers, while the control umbrellas are deployed in the upper atmosphere and support the whole system. The separation of the functions of doing work and keeping balance solves the problem of achieving the balance between doing work and body-balance well. The structure of the umbrella–ladder combination system is showed in Fig. 1.

As mentioned above, the tethers play an important role in the new design. It is through the tether tension that the wind can drive the ground-based generator mechanically. To extract the energy in the high altitude winds, the umbrellas should reach a certain high altitude, and the tethers are also kept aloft, exposed to atmospheric environment. When there is a thunderstorm, the tether will be besmirched, and the conductivity of the tether may increase. Hence if a lightning discharge occurs, there will be a possibility that the tether attracts the lightning leader to develop via it. Or the strong impulsive electric field generated by the lightning may cause a surface flashover along the tether. The strong static electric field generated by the accumulated charge in the thundercloud may also cause a breakdown on the tether. If the tether reaches the charge center of the cloud, new lightning may be triggered by the breakdown on the tether. The breakdown on the tether will also attract the lightning channel to approach. Whether a new lightning is triggered by the tether or the formed lightning channel attracted by the breakdown on tether, the breakdown could develops continually along the tether, finally throughout the tether and the current is conducted downward. If the strong lightning current is conducted via the tethers to the ground station, the current and the lightning high voltage accompanied will bring destruction to the upper system and the ground-base generator. In this case, analysis of the lightning characteristics of the tethers and the possibility of lightning discharge along the tethers is a very important issue for the system. Not only for the new high altitude wind energy exploitation system which adopt the new concept of umbrella–ladder combination system, but also for all high altitude wind energy exploitation systems which utilize nonconductive tethers to connect the upper part and the ground, the analysis is referable. This paper is structured as follows: firstly, the situation where a lightning occurs is described: the technical performance of the tethers in the system is detailed, the typical electrical charge structure and lightning occurrence in the thundercloud are described and the mechanism of the tethers trigging lightning under thunderstorm is analyzed; secondly, an experimental study of the lightning impulse characteristics of the tethers is presented and an analysis of the possibility of lightning flashover along the tether is undertaken; finally, the protection methods for the system are roughly researched. The paper is an expansion of our conference paper [12].

2. Lightning environment parameters and the function of the tether

2.1. The technical details of the transmission tethers

The tethers applied in the new system of extracting energy from high altitude winds are constructed by polyethylene polymer, the high strength insulated material. When the system is collecting the wind energy, the polyethylene polymer tethers are suspending in air. They connect the high altitude part and the generator on the ground, keep the umbrella–ladder combination system at a certain altitude, and drive the ground-based generator. It is through the tethers that the mechanical energy is transmitted to the ground and transformed to electric energy. Furthermore, the tethers constitute the tracks of the doing-work umbrellas which are driven by wind and slide along the tethers. The tethers also control contraction of the umbrella fabric so as to control the wind energy collected by the umbrella–ladder combination system, control the height of the wind energy absorber and the balance of the whole system. They construct the bones of the system and make it an organic whole.

2.2. The charge structure and lightning occurrence in the thunderstorm

As the first project adopting the new concept for extracting energy from high altitude winds has been installed on Jiaodong Peninsula, Shandong Province, China, and as the charge structure of the thundercloud there is a typical tripole-charge structure which can be most commonly seen in the world, the paper will describe the lightning environment parameters in Jiaodong Peninsula as the representative.

The tripole-charge structure is: there are three charge layers of different polarity and different density: the main positive charge region, the main negative charge region and the secondary positive charge region. The three layers are vertically arranged in the thundercloud: from top to bottom, the main positive charge region in the higher part of the thundercloud with temperature in the range from $-25\,^{\circ}\mathrm{C}$ to $-60\,^{\circ}\mathrm{C}$, the main negative charge region with temperature of $-10\,^{\circ}\mathrm{C}$ to $-25\,^{\circ}\mathrm{C}$, and the secondary positive charge region with temperature about $0\,^{\circ}\mathrm{C}$. The secondary positive charge region does not exist in a bipole-charge structure [13].

In Jiaodong Peninsula, at the mature stage of the thundercloud, as shown in Fig. 2, the charge density of the main positive