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Transient EMF induced in LV cables due to wind turbine direct lightning strike

Petar Sarajčev*, Ivan Sarajčev, Ranko Goić

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića bb, HR-21000 Split, Croatia

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ABSTRACT

This paper presents a novel, easy to use, engineering method for determining the transient electromotive force (EMF) induced in low-voltage (LV) cables, connecting the wind turbine with a near-by transformer, in the event of direct lightning strike into the top of the wind turbine tower. Proposed method is based on the application of the travelling wave analysis onto the system consisted of wind turbine tower, earthing system of wind turbine, earthing system of near-by transformer station and LV cables connecting the wind turbine with associated transformer. Hence, this design gives rise to a complex, mutually connected, earthing system. Direct lightning strike to the wind turbine initiates a travelling wave process in the system consisted of lightning channel, wind turbine tower and earthing system of the wind turbine. Due to the transient nature of the observed phenomenon, current and voltage states at the earthing system as well as in the associated low-voltage cables are formed through the propagation and reflection of the accompanying travelling waves. Transient EMF induced in LV cables could endanger cable main insulation and insulation of the associated transformer LV winding. Developed theory is subsequently applied on the concrete wind turbine example.

1. Introduction

Wind turbines regularly present tall, isolated objects. Typical modern wind turbines have a rated power in the range of 1–2.5 MW with typical tower height 50–100 m. Length of one blade can reach 60 m. The large size, distinctive shape and the fact that they are open-air structures placed in often isolated, mountainous conditions means that they are vulnerable to lightning strikes. Areas of favourable locations for wind turbines usually coincide with areas of thunderstorm activity, which has been confirmed, amid others, by NASA report [1]. This report shows that in most areas where wind density is high, there are 30 or more thunderstorm days per year [1,2]. Wind turbine blades are by far the most likely points of direct lightning strike. However, almost any part of the turbine is susceptible to direct lightning strike. In a study completed in 2002, the National Renewable Energy Association statistics showed that up to 8 out of 100 wind turbines could be expected to receive one direct lightning strike every year [2,3]. Between 1992 and 1995, Germany alone reported 393 incidents of lightning damage to wind turbines, of which a 124 direct lightning strikes to the wind turbine [2,4].

Apart from serious damage to blades, breakdown of low-voltage and control circuits have frequently occurred in many wind farms throughout the world. According to IEC TR61400-24 [5], the most frequent failures, more than 50%, in wind turbine equipment are those occurring in low-voltage (LV), control, and communication circuits. Currently, available statistics reveal that between 4% and 8% of European wind turbines are damaged by lightning every year [6]. This situation is even worse in southern parts of Europe, due to the increased thunderstorm activity. Should lightning damage a wind turbine, production will be lost and expensive repairs may have to be carried out.

Typical wind turbine design, from the point of view of LV/MV transformer housing, can be divided in two categories: wind turbines with transformer housed at the base of the tower and wind turbines with transformer housed in a near-by object. This object (transformer station) provides a space for the transformer itself and other electrical equipment (MV switchgear and low-voltage installations). Hence, transformer station is connected with cables to the near-by wind turbine. This situation is graphically shown in Fig. 1.

Direct lightning strike to the wind turbine tower results with a complicated transient phenomenon, whose numerical solution procedures tend to be rather involved. Several sophisticated numerical procedures have been developed in recent years, which could account for the various phenomena that accompany such a lightning stroke occurrences. An excellent overview of the available numerical methods for the solution of the mentioned problems could be found in [7]. Treatment of the phenomena associated with direct lightning stroke, adopted in this paper, is confined to the basic engineering model. More advanced treatments could be found in e.g. [8,9]. Direct lightning strike to the wind turbine

* Corresponding author. Tel.: +385 21 305 806/725/736; fax: +385 21 463 877.
E-mail addresses: petar.sarajcev@fesb.hr (P. Sarajčev), ivan.sarajcev@fesb.hr (I. Sarajčev), rango.goic@fesb.hr (R. Goić).

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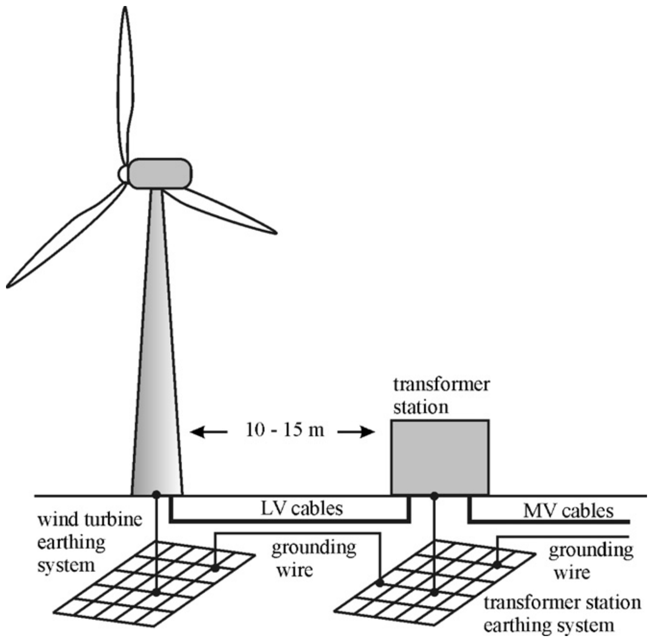

Fig. 1. Graphical depiction of wind turbine design, with transformer housed in a near-by transformer station.

initiates a travelling wave process in the following system: lightning channel – wind turbine tower – earthing system of the wind turbine. Accompanying current and voltage states are established through the propagation of current and voltage travelling waves [10]. Due to the wave nature of the observed phenomenon, lightning channel and wind turbine tower need to be represented with their surge impedances. Complexity of the lightning channel and tower representation vary significantly between different models. Here, antenna theory models feature prominently in frequency domain solutions [11], while finite difference time domain (FTDT) models feature prominently in time domain treatment of the lightning stroke [12]. Usually, wind turbine tower could be sufficiently accurately represented as a uniform lossless transmission line. Additional issues concerning lightning strikes to tall isolated towers, which might need to be accounted for in some cases, are presented in [13]. Earthing system of the wind turbine, due to associated transient phenomena, needs to be represented with the impulse/surge impedance. Deriving adequate representation of the earthing system, during lightning strikes, is in itself a difficult and complicated procedure. Several numerical models have been established in order to alleviate the solution to this complex task. Some noteworthy examples could be found in [14–16]. A sophisticated numerical model, derived in [17], is employed in this paper in order to determine the impulse impedances of the wind turbine grounding systems. During the lightning surge current dissipation process, self and mutual impedances of the wind turbine earthing system feature prominently, as well as soil ionization.

In case of transformer being housed in a near-by object, considered earthing system is consisted of two separate and mutually connected earthing systems: earthing of the wind turbine and earthing of the near-by transformer station (object). These two grounding systems are usually very close to each other. Their near-by outer limits separate a distance which is approximately in the range of the tower footing dimensions (ca. 10 m). Connection between these two earthing systems is established with a grounding wire. Low-voltage cables connect wind turbine to the transformer in the near-by object, as shown in Fig. 1. Those are usually single core cable systems without metallic screen. Additionally, MV transformer side is connected through MV cables to the main MV/HV transformer station. Grounding wire is laid along-side these MV cables and connected to the transformer station earthing systems. Medium-voltage cables and associated grounding wire is also shown in Fig. 1.

During the direct lightning strike, multiple reflections of the initiated travelling wave occur at each surge impedance discontinuity points [10]. Discontinuity points in the observed system are: point of direct lightning strike and connection point of wind turbine tower and earthing system. This last point is especially important. Transient potential rise of the wind turbine earthing system is established at this point.

Computation of the wind turbine earthing system transient potential rise will be described in this paper. This potential gives rise to the induced current in the grounding wire connecting two earthing systems. This transient current subsequently, due to electromagnetic coupling, induces transient voltage (electromotive force) in the low-voltage cables, connecting the wind turbine with a LV/MV transformer. Computation of this induced EMF in low-voltage cables will be presented in this paper as well. This transient EMF stresses both the main cable insulation and insulation of the transformer LV winding. This induced transient EMF can, thus, damage the LV/MV transformer windings and/or other sensitive equipment found in the near-by transformer station.

Main objective of this paper could be seen in establishing the fact that direct lightning strikes into the wind turbine tower, with relatively moderate current amplitude and surge front duration, can give rise to large induced transient EMF in a LV cables connecting this wind turbine to a near-by transformer station. This transient EMF induced in LV cable system can damage the transformer LV winding, in case of inadequate or non-existent overvoltage protection. Hence, it will be shown that here presented analysis could form a part of overvoltage protection selection procedure for wind turbines, which have transformer housed in a near-by object and connected with LV cables.

2. Mathematical model

Fig. 2 graphically depicts a situation of direct lightning strike into the wind turbine tower. Earthing systems of the wind turbine and near-by transformer station, as well as grounding wire connecting two earthing systems are also shown in Fig. 2. Time instant of the lightning strike is noted with $t = 0$, while position of the strike is marked with $x = 0$.

Symbols used in Fig. 2 have following meanings:

$i(t)$ – lightning surge current (kA),
H – height of the wind turbine tower (m),
Z_t – wind turbine tower surge impedance (Ω),
R_{WT} – surge impedance of the wind turbine earthing system (Ω),
R_{TS} – surge impedance of the transformer station earthing system, which includes transient impedance of grounding wire laid along-side MV cables (Ω),
R_m – mutual impedance between earthing systems of wind turbine and transformer station, due to the conductive coupling (Ω),
$V_g(t)$ – transient potential of wind turbine earthing system in respect to the neutral ground (kV),
$I_g(t)$ – transient current dissipated in to earth through the wind turbine earthing system (kA),
$I_{TS}(t)$ – part of the transient current flowing through the grounding wire which is connecting the two earthing systems (kA).

It needs to be stated that lightning surge currents with modest parameters (low values of amplitude and low steepness of the surge front) will be hereafter treated. This is in accordance with previously stated facts concerning the intention of this paper. Due to afore mentioned observations, soil ionization of the associated