Electric Power Systems Research 139 (2016) 16–21

Contents lists available at ScienceDirect

Electric Power Systems Research

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

A one-dimensional thermo-hydrodynamic model for upward leader inception considering gas dynamics and heat conduction

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ARTICLE INFO

Article history:
Received 31 March 2015
Received in revised form 20 October 2015
Accepted 26 November 2015
Available online 15 January 2016

Keywords:
Upward leader
Modified thermo-hydrodynamic model
Gas dynamics
Heat conduction
Mach–Zehnder interferometer

ABSTRACT

Modeling of upward leader inception is important for lightning risk assessment of high voltage transmission systems. The classical thermodynamic model for long gap leader discharge proposed by Gallimberti has been widely adopted for about 30 years and applied to the analysis of unstable upward leader inception, taking gas temperature rising to 1500 K as the criterion. However, the gas dynamic process and heat conduction which have influences on the gas temperature and leader diameter are not fully considered in this model. Theoretical analysis and simplified simulation illustrated that there are a few limitations without taking the two factors into account. In this paper, the gas dynamics and heat conduction have been considered, and a modified one-dimensional thermo-hydrodynamic (1D-THD) model has been proposed to calculate the inception of upward leader. This model also applies to leader channel expansion. Besides, a Mach–Zehnder interferometer was set up to observe the gas density variation and radial expansion of heated leader channels. The calculation results of the channel expansion have good agreements with experimental data.

1. Introduction

Lightning shielding failure is the major cause of high voltage transmission lines outage. The electro-geometric model (EGM) proposed in 1960s is the most traditional and effective method in lightning risk assessment [1,2]. However, the evaluation accuracy for EHV/UHV transmission lines is not always satisfactory. Based on the theory of lightning leader progress and long air gap discharges, the leader progression model (LPM) was put forward [3]. Upward leader is one of the most important parts in the LPM, and the inception criterion of upward leader is a key element.

Since 1960s, several criteria are proposed for analyzing the inception of long air gap leaders. One of them is the critical radius criterion which is used in Dellera and Garbagnati's model [3]. Another is the voltage inception criterion which was proposed by Rizk [4]. Peter and Waters also proposed the critical length criterion [5]. These criteria have been proven to be in good agreement with the experimental results for the discharges in long air gaps. However, it has some restrictions to use these criteria in the analysis of upward leaders emerging from the HVDC and UHVDC transmission lines, as the space charge due to the pre-existing voltage was not taken into consideration.

For overcoming these restrictions, a more sophisticated inception criterion was proposed by Gallimberti and Lalande [6,7] based on the heating processes inside stems and leaders, taking gas temperature of 1500 K as the critical value. In the self-consistent upward leader model proposed by Becerra and Cooray [8], this criterion was used to determine the inception of unstable upward leader. However, the gas dynamics and heat conduction were not fully considered in this criterion, which will make the calculated temperature of the stem and leader channel higher than the real situation.

This paper is an extended version of [9]. A simplified one-dimensional thermo-dynamic (1D-THD) model for upward leader inception considering gas dynamic process and heat conduction was proposed, on the basis of the model proposed by Gallimberti. The modified model reflects the radial distribution of gas density, gas temperature and pressure in leader channels, and calculation results can also illustrate the channel expansion. The diameter variation of leader channels is consistent with the experimental data obtained by Mach–Zehnder interferometry.

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http://dx.doi.org/10.1016/j.epsr.2015.11.028
0378-7796/

2. Deficiency of the classical leader model

2.1. Classical thermodynamic model

The model for leader inception proposed by Gallimberti is shown in (1) [6],

$$\begin{cases} \dfrac{d}{dt}(W_v(T_v)) = f_v EI - \dfrac{W_v(T_v) - W_v(T_h)}{\tau_{vt}} \\ \dfrac{d}{dt}(H_t(T_h)) = (f_e + f_r + f_t)EI + \dfrac{W_v(T_v) - W_v(T_h)}{\tau_{vt}} \\ W_v(T) = n_h \pi a^2 \dfrac{\varepsilon_v}{\exp(\varepsilon_v/kT) - 1} \\ H_t(T_h) = \dfrac{7}{2} k T_h n_h \pi a^2 \end{cases} \quad (1)$$

where, E, I, a and n_{h} are the E-field strength, conduction current, leader initial radius and heavy particles density. H_{t} is the thermal enthalpy, $W_{\mathrm{v}}(T)$ is the vibrational energy corresponding to the temperature T, τ_{vt} is the time constant for vibrational relaxation depending on both gas temperature and air humidity, k is the Boltzmann constant, f_{v}, f_{t}, f_{e} and f_{r} are the fractions of the total electron energy transferred to neutral molecules in different forms (v-vibration, t-translation, e-electronic excitation, r-rotation), as functions of the reduced field E/n_{h}. T_{v} is the vibrational temperature and T_{h} is the gas temperature which the criterion focus on. When the gas temperature T_{h} of the stem is heated from 1500 K to 2000 K, the leader is considered to initiate. The critical value of gas temperature was usually chosen 1500 K.

The classical model is zero-dimensional, without considering any distribution of parameters inside plasma channel. In this model, the mass within the plasma cylinder is assumed to be constant ($n_{\mathrm{h}}\pi a^2$ = constant), and the pressure inside the channel is assumed to keep an atmosphere. Thus, the thermal enthalpy is only a function of gas temperature and depends on the energy input by current and vibrational relaxation. Besides, heat losses caused by conduction and radiation are neglected in this model.

2.2. Analysis of gas dynamics

The basic equations to describe ideal gas dynamics without considering gravity, viscosity and heat conduction are shown in (2), consisting of the mass equation, momentum equation and energy equation,

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \\ \dfrac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} = -\dfrac{1}{\rho}\nabla p \\ \dfrac{\partial}{\partial t}(e + \dfrac{v^2}{2}) + \vec{v} \cdot \nabla (e + \dfrac{v^2}{2}) = -\dfrac{1}{\rho}\nabla \cdot (p\vec{v}) + q \end{cases} \quad (2)$$

where, ρ is gas mass density, v is flow velocity, e is internal energy density, p is gas pressure and q is energy injection. The energy equation in (2) can also be expressed as (3), where, h is the thermal enthalpy density.

$$\frac{\partial}{\partial t}(h + \frac{v^2}{2}) + \vec{v} \cdot \nabla (h + \frac{v^2}{2}) = -\frac{1}{\rho}\frac{\partial p}{\partial t} + q \quad (3)$$

In the classical model, the pressure variation inside the plasma channel is neglected, as the mass equation and momentum equation to describe gas dynamic process were not included. Besides, the energy transferred from internal form to dynamic form was neglected (v = 0). Then the energy equation (3) is simplified tothe second equation in (1), taking the molecules inside the plasma channel as a whole.

To analyze the effects of gas dynamics, a simplified simulation was conducted. We considered a gas cylinder, with 0.3 mm radius. The initial temperature of the cylinder is 25° (298.15 K) and the initial pressure is 1 atm. An energy impulse is injected into the cylinder in an infinite short period (τ = 0) at time 0 (t = 0), heating the cylinder to a center gas temperature of 3000 K and a radial distribution of cubic function (the average temperature of the cylinder is about 1060 K). Thus, the pressure in the center of the gas cylinder reaches 10 atm. and the gas density in the cylinder keeps the initial value at t = 0. The amount of energy input in this example is similar to that from a discharge current impulse with several μC. We calculated the pressure relaxation process of the high temperature gas cylinder. The results of gas mass density, gas temperature and pressure variation in 2 μs are shown in Fig. 1, where, ρ_0 is the mass density of ambient air. The channel expands from 0.3 mm to 0.5 mm in radius after 2 μs and the average gas temperature decreases to about 700 K. The pressure relaxation period is about 1 μs, which is shorter or comparable with the duration of stem-leader transition. The calculation results indicate that when large impulse energy injects in a short period, the overpressure inside the heated channel is considerable, and the pressure relaxation period cannot be neglected in the leader inception stage.

In practice, the duration of discharge current impulses are usually varied from hundreds of nanoseconds to a few microseconds, instead of an infinitely short period. We change the duration τ of the energy impulse injected to the gas cylinder with the same amount and radial distribution as above, and the pressure variation at the center of the gas cylinder as function of time is shown in Fig. 2. The results show that that the overpressure at the center of the heated gas cylinder is lower as the duration of the injected energy impulse is longer. When τ is 1 μs, the injected power is similar with that from several amperes current, which is common in long gap discharge. In this condition, the overpressure is still considerable and the pressure relaxation period is close to the duration of the injected energy. The calculation further clarifies that there are a few restrictions without considering the pressure variation and gas dynamics into the leader inception model.

2.3. Analysis of heat loss

The thermal energy transfer through a section via heat conduction can be described by the Fourier law as (4),

$$\mathrm{d}E_{\mathrm{c}} = -\kappa \frac{\partial T_{\mathrm{h}}}{\partial z} \mathrm{d}A \quad (4)$$

where, E_{c} is the energy transfer due to heat conduction, κ is the thermal conductivity varied with temperature. A is the cross section area vertical to z direction.

The thermal conductivity κ of air at normal atmosphere temperature is fairly small and negligible. However, κ increases significantly as the gas temperature of leader channel reaches high values. The thermal conductivity κ of 3000 K air thermal plasma (LTE) was around 0.4 W m/K, while it was around 0.12 W m/K without considering dissociation and ionization caused by air temperature increment [10]. Simple estimation indicates that the average heat conduction loss of a leader channel with average temperature of 3000 K is about 5–15 kW per unit length ($\approx 2\pi\kappa T_{\mathrm{h}}$), which is comparable with the energy transition to gas temperature increasing due to electronic collisions in some occasions (e.g., 20 kW/m when $f_{\mathrm{t}} + f_{\mathrm{e}} + f_{\mathrm{r}}$ = 0.1, E = 4 kV/cm, I = 0.5 A). Thus, the heat conduction should be considered in the leader inception model, which makes the model more general. Gas dynamicequations