Lightning Physics and Lightning Protection

E M Bazelyan

and

Yu P Raizer

IoP

Institute of Physics Publishing
Bristol and Philadelphia

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

ISBN 0 7503 0477 4

Library of Congress Cataloging-in-Publication Data are available

Publisher: Nicki Dennis
Commissioning Editor: John Navas
Production Editor: Simon Laurenson
Production Control: Sarah Plenty
Cover Design: Victoria Le Billon
Marketing Executive: Colin Fenton

Published by Institute of Physics Publishing, wholly owned by The Institute of Physics, London

Institute of Physics Publishing, Dirac House, Temple Back, Bristol BS1 6BE, UK

US Office: Institute of Physics Publishing, The Public Ledger Building, Suite 1035, 150 South Independence Mall West, Philadelphia, PA 19106, USA

Typeset in 10/12pt Times by Academic + Technical, Bristol
Printed in the UK by J W Arrowsmith Ltd, Bristol

Contents

Preface

Today, we know sufficiently much about lightning to feel free from the mystic fears of primitive people. We have learned to create protection technologies and to make power transmission lines, skyscrapers, ships, aircraft, and spacecraft less vulnerable to lightning. Yes, the danger is getting less but it still exists! With every step of the technical progress, lightning arms itself with a new weapon to continue the war by its own rules against the self-confident engineer. As we improve our machines and stuff them with electronics in an attempt to replace human beings, lightning acts in an ever refined manner. It takes us by surprise where we do not expect it, making us feel helpless again for some time.

We do not intend to present in this book a set of universal lightning protection rules. Such a task would be as futile as advertising a universal antibiotic lethal to every harmful microbe. The world is changeable, and today's panacea often becomes a useless pill even before the advertising sheet fades. Technical progress has so far failed to take lightning unawares. Improvement and miniaturization of devices increase our concern about the refined destructive behaviour of lightning, but no prophet is able to foresee all of its destructive effects.

We do not plan to discuss in detail all available information on lightning. There are already some excellent books providing all sort of reference data, among them the two volumes of *Lightning* edited by R H Golde and *Lightning Discharge* by M Uman. Our aim is different. We think it important to give the reader some clear, up-to-date physical concepts of lightning development, which cannot be found in the books referred to. These will serve as a basis for the researcher and engineer to judge the properties of this tremendous gas discharge phenomenon. Then we shall discuss the nature of various hazardous manifestations of lightning, focusing on the physical mechanisms of interaction between lightning and an affected construction. The results of this consideration will further be used to estimate the effectiveness of conventional protective measures and to predict technical means for their improvement. We give, wherever possible, technical advice and recommendations. Our main goal, however, is to help the reader to make his own predictions by providing information on the whole arsenal of potentionally hazardous effects of lightning on a particular construction. We have often witnessed situations when an engineer was trying hard to 'impose' this or that protective device on an operating experimental structure which resisted his unnatural efforts. Ideally, the designer must be able to foresee all details of the relationship between lightning and the construction being designed. It is only in this case that lightning protection can become functionally effective and the protective device can be made compatible with the construction elements.

If an engineer is determined to follow this approach, both expedient and well-grounded, he will find this book useful. It is a natural extension of our previous book *Spark Discharge*, published by CRC Press in 1997, which dealt with streamer–leader breakdown of long gas gaps. The streamer–leader process is part of any lightning discharge when a plasma spark closes a gigantic air gap. Although the destructive effect of lightning is primarily due to the return stroke which follows the leader, it is the leader that makes the discharge channel susceptible to it. This is why we give an overview of the streamer–leader process, focusing on extremal estimations and presenting some new ideas. We hope that the second chapter will prove informative even for those familiar with our book of 1997.

Some results of the lightning investigation run in the Krzhizhanovsky Power Institute are used in the book. The authors would like to thank Dr B N Gorin and Dr A V Shkilev who kindly allowed us to use the originals of lightning photographs. We are also grateful to L N Smirnova for translation of this book.

Chapter 1

Introduction: lightning, its destructive effects and protection

If you want to observe lightning, the best thing to do is to visit a special lightning laboratory. Such laboratories exist in all parts of the globe except the Antarctic. But you can save on the travel if you just climb onto the roof of your own house to give a good field of vision. Better, fetch your camera. Even an ordinary picture can show details the unaided human eye often misses. You might as well sit back in your favourite armchair, having pulled it up to a window, preferably one overlooking an open space. The camera can be fixed on the window sill. There is nothing else to do but wait for a stormy night.

There is enough time for the preparations to be made because the storm will be approaching slowly. At first, the air will grow still, and it will get much darker than it normally is on a summer night. The cloud is not yet visible, but its approach can be anticipated from the soundless flashes at the horizon. They gradually pull closer, and the brightest of them can already be heard as delayed and yet amiable roaring. This may go on for a long time. It may seem that the cloud has stopped still or turned away, but suddenly the sky is ripped open by a fire blade. This is accompanied by a deafening crash, quite different from a cannon shot because it takes a much longer time. The first lightning discharge is followed by many others falling out of the ripped cloud. Some strike the ground while others keep on crossing the sky, competing with the first discharge in beauty and spark length. This is the right time to start observations: remove the camera shutter and try to take a few pictures.

1.1 Types of lightning discharge

The above recommendation to remove the camera shutter should be taken literally. Much information on lightning has been obtained from photographs taken with a preliminarily opened objective lens. It is important, however, that

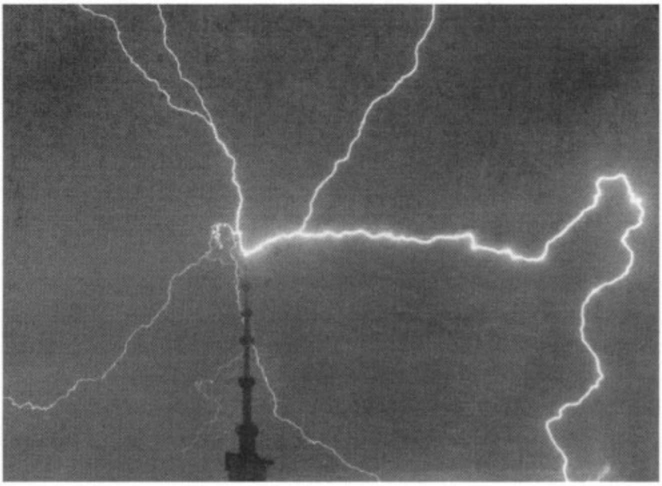

Figure 1.1. A static photograph of a lightning stroke at the Ostankino Television Tower in Moscow.

no other bright light source should be present within the vision field of the camera lens. The film can then be exposed for many minutes until a spark finds its way into the frame. After this, the lens should be closed with the shutter and the camera should be set ready for another shot. Experience has shown that at least one third of pictures taken during a good night thunderstorm prove successful.

All lightning discharges can be classified, even without photography, into two groups – intercloud discharges and ground strikes. The frequency of the former is two or three times higher than that of the latter. An intercloud spark is never a straight line, but rather has numerous bends and branchings. Normally, the spark channel is as long as several kilometres, sometimes dozens of kilometres.

The length of a lightning spark that strikes the ground can be defined more exactly. The average cloud altitude in Europe is close to three kilometres. Spark channels have about the same average length. Of course, this parameter is statistically variable, because a discharge from a charged cloud centre may start at any altitude up to 10 km and because of a large number of spark bends. The latter are observable even with the unaided eye. In a photograph, they may look strikingly fanciful (figure 1.1). A photograph can show another important feature inaccessible to the naked eye – the main bright spark reaching the ground has numerous branches which have stopped their development at various altitudes. A single branch may have a length comparable with that of the principal spark channel (figure 1.2).

Branches can be conveniently used to define the direction of lightning propagation. Like a tree, a lightning spark branches in the direction of

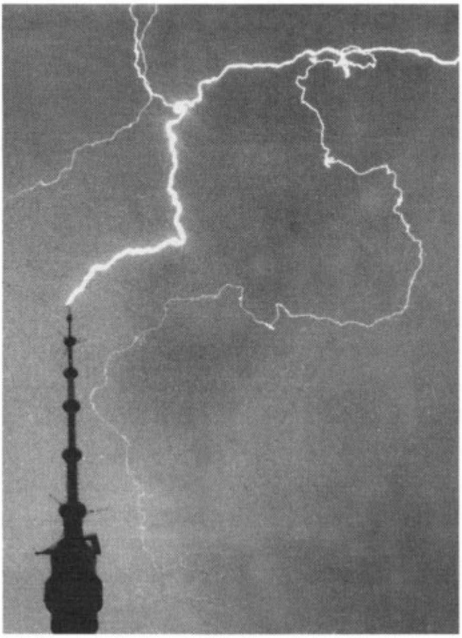

Figure 1.2. A photograph of a descending lightning with numerous branches.

growth. In addition to descending sparks outgrowing from a cloud toward the ground, there are also ascending sparks starting from a ground construction and developing up to a cloud (figure 1.3). Their direction of growth is well indicated by branches diverging upward.

In a flat country, an ascending spark can arise only from a skyscraper or a tower of at least 100–200 m high, and the number of ascending sparks grows with the building height. For example, over 90% of all sparks that strike the 530-m high Ostankino Television Tower in Moscow are of the ascending type [1]. A similar value was reported for the 410-m high Empire State Building in New York City [2]. Buildings of such a height can be said to fire lightning sparks up at clouds rather than to be attacked by them. In mountainous regions, ascending sparks have been observed for much lower buildings. As an illustration, we can cite reports of storm observations made on the San Salvatore Mount in Switzerland [3]. The receiving tower there was only 70 m high but most of the discharges affecting it were of the ascending type.

Skyscrapers and television towers are, however, quite scarce on the Earth. So the researcher has a natural desire to construct, in the right place and for a short time, a spark-generating tower of his own. For this, a small probe pulling up a thin grounded wire is launched towards a

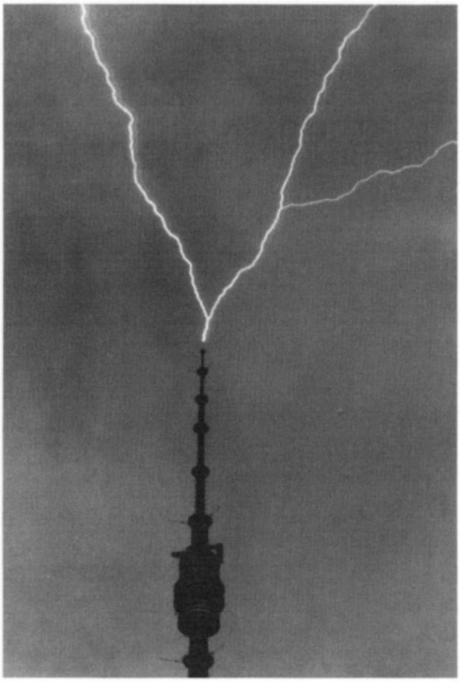

Figure 1.3. A photograph of an ascending lightning.

storm cloud [4]. When the probe rises to 200–300 m above the earth, an ascending spark is induced from it. A discharge artificially induced in the atmosphere is often referred to as triggered lightning. To raise the chances for a successful experiment, the electric field induced by the storm charges at the ground surface are measured prior to the launch. The probe is triggered when the field strength becomes close to 200 V/cm, which provides spark ignition in 60–70% of launches [5].

The value 200 V/cm is two orders of magnitude smaller than the threshold value of $E = 30\,\mathrm{kV/cm}$, at which a short air gap with a uniform field is broken down under normal atmospheric conditions. Clearly, no spark ignition would be possible without the local field enhancement by electric charges induced on the probe and the wire. Below, we shall discuss the triggered discharge mechanism in more detail.

A field detector on the Earth's surface (it might as well be placed on the window of your own room) can easily determine the polarity of the charge transported by a lightning spark to the ground. The polarity of the spark is defined by that of the charge. About 90% of descending sparks occurring in Europe during summer storms carry a negative charge, so these are known as negative descending sparks. The other descending sparks are positive. The proportion of positive sparks has been found to be somewhat larger in tropical and subtropical regions, especially in winter, when it may be as large as 50%.

There is no special name for lightning sparks generated by aircraft during flights, when they are entirely insulated from the ground. Such discharges arise fairly frequently. A modern aircraft experiences at least one lightning stroke every 3000 flight hours. Almost half of the strokes start from the aircraft itself, not from a cloud. This often happens in heap rather than clouds carrying a relatively small electric charge. The reason for a discharge from a large ground-insulated object is principally the same as from a grounded object and is due to the electric field enhancement by surface polarization charge. This issue will be discussed after the analysis of ascending sparks in section 4.2.

1.2 Lightning discharge components

An observer can notice a lightning spark flicker which, sometimes, may become quite distinct. Even the first cinematographers knew that the human eye could distinguish between two events only if they occurred with a time interval longer than 0.1 s. Since lightning flicker is observable, the pause between two current impulses must be longer than 0.1 s.

A current-free pause can be measured quite accurately by exposing a moving film to a lightning discharge. With up-to-date lenses and photographic materials, one can obtain a good 1 mm resolution of the film. In order to displace an image by 1 mm over a time period of 0.1 s, the film speed must be about 1 cm/s. It can be achieved by manually moving the film keeping the camera lens open (alas, an electrically driven camera is unsuitable for this). Then, with some luck, one may get a picture like the one in figure 1.4. The spark flashes up and dims out several times. Unless the pause is too long, a new flash follows the previous trajectory; otherwise, the spark takes a partially or totally new path.

A lightning spark with several flashes is known as a multicomponent spark. One may suggest that the channel of the first component formed in unperturbed air differs in its basic characteristics from the subsequent channels, if they take exactly the same path through the ionized and heated air. The formation of subsequent components is considered in sections 4.7 and 4.8. Note only that multicomponent sparks are usually negative, both ascending and descending. The average number of components is close to three, while the maximum number may be as large as thirty. Generally, the average duration of a lightning flash is 0.2 s and the maximum duration is 1–1.5 s [6], so it is not surprising that the eye can sometimes distinguish between individual components. Positive sparks normally contain only one component.

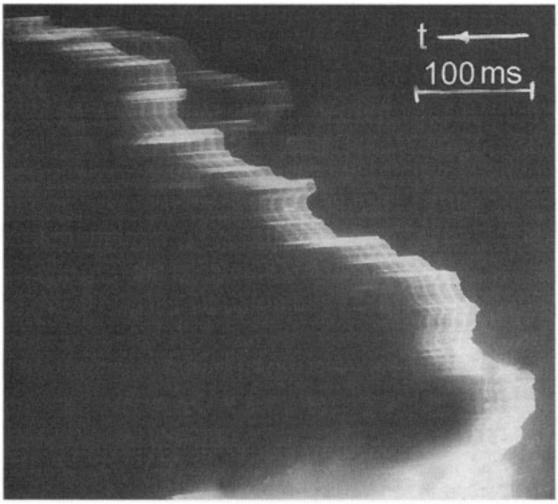

Figure 1.4. The image of a multicomponent lightning in a slowly moving film.

1.3 Basic stages of a lightning spark

The affinity of lightning to a spark discharge was demonstrated by Benjamin Franklin as far back as the 18th century. Historically, basic spark elements were first identified in lightning, and only much later were they observed in laboratory sparks. This is easy to understand if one recalls that a lightning spark has a much greater length and takes a longer time to develop, so that its optical registration does not require the use of sophisticated equipment with a high space and time resolution. The first streak photographs of lightning, taken in the 1930s by a simple camera with a mechanically rotated film (Boys camera), are still impressive [7]. They show the principal stages of the lightning process – the leader stage and the return stroke.

The leader stage represents the initiation and growth of a conductive plasma channel – a leader – between a cloud and the earth or between two clouds. The leader arises in a region where the electric field is strong enough to ionize the air by electron impact. However, it mostly propagates through a region in which the external field induced by the cloud charge does not exceed several hundreds of volts per centimetre. In spite of this it does propagate, which means that there is an intensive ionization occurring in its tip region, changing the neutral air to a highly conductive plasma. This becomes possible because the leader carries its own strong electric field induced by the space charge concentrated at the leader tip and transported together with it. A rough analogue of the leader field is that of a metallic needle connected with a thin wire to a high voltage supply. If the needle is sharp enough, the electric field in the vicinity of its tip will be very strong