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IEEE Guide for Direct Lightning Stroke Shielding of Substations

IEEE Power and Energy Society

Sponsored by the
Substations Committee

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3 Park Avenue
New York, NY 10016-5997
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30 April 2013

IEEE Std 998™-2012
(Revision of
IEEE Std 998-1996)

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IEEE Std 998-1996)

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Approved 5 December 2012

IEEE-SA Standards Board

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Figure 2 adapted from *Electrical Transmission and Distribution Reference Book,* by Central Station Engineers of the Westinghouse Electric Corporation, 4th ed., East Pittsburgh, PA, 1964.

Figures 6, 8, and 9 from MacGorman, D. R., M. W. Maier, and W. D. Rust, "Lightning Strike Density for the Contiguous United States from Thunderstorm Duration Record," report no. NUREG/CR-3759, National Oceanic and Atmospheric Administration, Norman, OK, May 1984.

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Figure 46 from CIGRE Task Force 33.01.03, "Lightning Exposure of Structures and Interception Efficiency of Air Terminals," Paris: CIGRE, Technical Brochure 118, Oct. 1997.

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Abstract: Design information for the methods historically and typically applied by substation designers to reduce direct lightning strokes to equipment and buswork within substations is provided. Two approaches, the classical empirical method and the electrogeometric model, are presented in detail. A third approach, which involves the use of non-conventional lightning terminals and related design methods, is also reviewed.

Keywords: collection volume method (CVM), direct stroke shielding, electro-geometric model (EGM), field intensification factor method (FIFM), fixed angle, IEEE 998™, leader inception theory (LIT), leader progression model (LPM), lightning stroke protection, self-consistent leader inception and propagation model (SLIM), substations empirical curves

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PDF: ISBN 978-0-7381-8037-3 STD98031
Print: ISBN 978-0-7381-8038-0 STDPD98031

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Introduction

This introduction is not part of IEEE Std 998™-2012, IEEE Guide for Direct Lightning Stroke Shielding of Substations.

Work on the original guide began in 1973 and many former members made contributions toward its completion.

Working Group D5 of the IEEE PES Substations Committee began updating the guide in 2008. This guide provides information about various shielding methodologies to estimate and design direct lightning stroke shielding for outdoor substations. Calculation details, design estimates, and generally accepted practices for substation shielding designs are provided. This guide can be beneficial for engineers in evaluating direct lightning stroke shielding design for outdoor substations.

Dedication

This revision of IEEE Std 998 is dedicated to the memory of Gary R. Engmann. Gary through his membership in this working group and many others was always in the forefront with his statement "that the purpose of a guide is to disseminate information to practicing engineers." Gary had a long association and leadership with the IEEE Substations Committee, NESC, IEEE-SA, and many other Technical Committees and Working Groups. He did not back away from tasks whether controversial or not. His leadership of the IEEE 998 "Bucket Brigade" was an insightful contribution to the development of this revision. His knowledge, humor, and keen insight into the day-to-day needs of all of us will be sorely missed.

Contents

IEEE Guide for Direct Lightning Stroke Shielding of Substations

1. Overview

1.1 Scope

This guide identifies and discusses design procedures to provide direct stroke shielding of outdoor distribution, transmission, and generating plant substations. Known methods of shielding from direct strokes were investigated during the preparation of this guide, and information is provided on two methods found to be widely used:

a) The classical empirical method

b) The electrogeometric model

A third approach, which involves the use of non-conventional lightning terminals and related design methods, is also reviewed.

This guide does not purport to include all shielding methods that may have been developed. The guide also does not address protection from surges entering a substation over power or communication lines or the personnel safety issues.

Users of this guide should thoroughly acquaint themselves with all factors that relate to the design of a particular installation and use good engineering judgment in the application of the methods given here, particularly with respect to the importance and value of the equipment being protected.