ENGENHARIA ELÉTRICA:

COMUNICAÇÃO INTEGRADA NO UNIVERSO DA ENERGIA

João Dallamuta
Henrique Ajuz Holzmann
(Organizadores)

Atena
Editora
Ano 2021

ENGENHARIA ELÉTRICA:

COMUNICAÇÃO INTEGRADA NO UNIVERSO DA ENERGIA

João Dallamuta
Henrique Ajuz Holzmann
(Organizadores)

Atena
Editora
Ano 2021

Editora Chefe
Profª Drª Antonella Carvalho de Oliveira
Assistentes Editoriais
Natalia Oliveira
Bruno Oliveira
Flávia Roberta Barão
Bibliotecária
Janaina Ramos
Projeto Gráfico e Diagramação
Natália Sandrini de Azevedo
Camila Alves de Cremo
Luiza Alves Batista
Maria Alice Pinheiro
Imagens da Capa
Shutterstock
Edição de Arte
Luiza Alves Batista
Revisão
Os Autores

2021 *by Atena Editora*
Copyright © Atena Editora
Copyright do Texto © 2021 Os autores
Copyright da Edição © 2021 Atena Editora
Direitos para esta edição cedidos à Atena Editora pelos autores.

Todo o conteúdo deste livro está licenciado sob uma Licença de Atribuição *Creative Commons*. Atribuição-Não-Comercial-NãoDerivativos 4.0 Internacional (CC BY-NC-ND 4.0).

O conteúdo dos artigos e seus dados em sua forma, correção e confiabilidade são de responsabilidade exclusiva dos autores, inclusive não representam necessariamente a posição oficial da Atena Editora. Permitido o *download* da obra e o compartilhamento desde que sejam atribuídos créditos aos autores, mas sem a possibilidade de alterá-la de nenhuma forma ou utilizá-la para fins comerciais.

Todos os manuscritos foram previamente submetidos à avaliação cega pelos pares, membros do Conselho Editorial desta Editora, tendo sido aprovados para a publicação com base em critérios de neutralidade e imparcialidade acadêmica.

A Atena Editora é comprometida em garantir a integridade editorial em todas as etapas do processo de publicação, evitando plágio, dados ou resultados fraudulentos e impedindo que interesses financeiros comprometam os padrões éticos da publicação. Situações suspeitas de má conduta científica serão investigadas sob o mais alto padrão de rigor acadêmico e ético.

Conselho Editorial
Ciências Humanas e Sociais Aplicadas
Prof. Dr. Alexandre Jose Schumacher – Instituto Federal de Educação, Ciência e Tecnologia do Paraná
Prof. Dr. Américo Junior Nunes da Silva – Universidade do Estado da Bahia
Prof. Dr. Antonio Carlos Frasson – Universidade Tecnológica Federal do Paraná

Atena
Editora
Ano 2021

Prof. Dr. Antonio Gasparetto Júnior – Instituto Federal do Sudeste de Minas Gerais
Prof. Dr. Antonio Isidro-Filho – Universidade de Brasília
Prof. Dr. Carlos Antonio de Souza Moraes – Universidade Federal Fluminense
Prof. Dr. Crisóstomo Lima do Nascimento – Universidade Federal Fluminense
Profª Drª Cristina Gaio – Universidade de Lisboa
Prof. Dr. Daniel Richard Sant'Ana – Universidade de Brasília
Prof. Dr. Deyvison de Lima Oliveira – Universidade Federal de Rondônia
Profª Drª Dilma Antunes Silva – Universidade Federal de São Paulo
Prof. Dr. Edvaldo Antunes de Farias – Universidade Estácio de Sá
Prof. Dr. Elson Ferreira Costa – Universidade do Estado do Pará
Prof. Dr. Eloi Martins Senhora – Universidade Federal de Roraima
Prof. Dr. Gustavo Henrique Cepolini Ferreira – Universidade Estadual de Montes Claros
Profª Drª Ivone Goulart Lopes – Istituto Internazionele delle Figlie de Maria Ausiliatrice
Prof. Dr. Jadson Correia de Oliveira – Universidade Católica do Salvador
Prof. Dr. Julio Candido de Meirelles Junior – Universidade Federal Fluminense
Profª Drª Lina Maria Gonçalves – Universidade Federal do Tocantins
Prof. Dr. Luis Ricardo Fernandes da Costa – Universidade Estadual de Montes Claros
Profª Drª Natiéli Piovesan – Instituto Federal do Rio Grande do Norte
Prof. Dr. Marcelo Pereira da Silva – Pontifícia Universidade Católica de Campinas
Profª Drª Maria Luzia da Silva Santana – Universidade Federal de Mato Grosso do Sul
Profª Drª Paola Andressa Scortegagna – Universidade Estadual de Ponta Grossa
Profª Drª Rita de Cássia da Silva Oliveira – Universidade Estadual de Ponta Grossa
Prof. Dr. Rui Maia Diamantino – Universidade Salvador
Prof. Dr. Urandi João Rodrigues Junior – Universidade Federal do Oeste do Pará
Profª Drª Vanessa Bordin Viera – Universidade Federal de Campina Grande
Prof. Dr. William Cleber Domingues Silva – Universidade Federal Rural do Rio de Janeiro
Prof. Dr. Willian Douglas Guilherme – Universidade Federal do Tocantins

Ciências Agrárias e Multidisciplinar
Prof. Dr. Alexandre Igor Azevedo Pereira – Instituto Federal Goiano
Profª Drª Carla Cristina Bauermann Brasil – Universidade Federal de Santa Maria
Prof. Dr. Antonio Pasqualetto – Pontifícia Universidade Católica de Goiás
Prof. Dr. Cleberton Correia Santos – Universidade Federal da Grande Dourados
Profª Drª Daiane Garabeli Trojan – Universidade Norte do Paraná
Profª Drª Diocléa Almeida Seabra Silva – Universidade Federal Rural da Amazônia
Prof. Dr. Écio Souza Diniz – Universidade Federal de Viçosa
Prof. Dr. Fábio Steiner – Universidade Estadual de Mato Grosso do Sul
Prof. Dr. Fágner Cavalcante Patrocínio dos Santos – Universidade Federal do Ceará
Profª Drª Girlene Santos de Souza – Universidade Federal do Recôncavo da Bahia
Prof. Dr. Jael Soares Batista – Universidade Federal Rural do Semi-Árido
Prof. Dr. Júlio César Ribeiro – Universidade Federal Rural do Rio de Janeiro
Profª Drª Lina Raquel Santos Araújo – Universidade Estadual do Ceará
Prof. Dr. Pedro Manuel Villa – Universidade Federal de Viçosa
Profª Drª Raissa Rachel Salustriano da Silva Matos – Universidade Federal do Maranhão
Prof. Dr. Ronilson Freitas de Souza – Universidade do Estado do Pará
Profª Drª Talita de Santos Matos – Universidade Federal Rural do Rio de Janeiro
Prof. Dr. Tiago da Silva Teófilo – Universidade Federal Rural do Semi-Árido

Atena
Editora
Ano 2021

Prof. Dr. Valdemar Antonio Paffaro Junior – Universidade Federal de Alfenas

Ciências Biológicas e da Saúde
Prof. Dr. André Ribeiro da Silva – Universidade de Brasília
Profª Drª Anelise Levay Murari – Universidade Federal de Pelotas
Prof. Dr. Benedito Rodrigues da Silva Neto – Universidade Federal de Goiás
Profª Drª Débora Luana Ribeiro Pessoa – Universidade Federal do Maranhão
Prof. Dr. Douglas Siqueira de Almeida Chaves – Universidade Federal Rural do Rio de Janeiro
Prof. Dr. Edson da Silva – Universidade Federal dos Vales do Jequitinhonha e Mucuri
Profª Drª Elizabeth Cordeiro Fernandes – Faculdade Integrada Medicina
Profª Drª Eleuza Rodrigues Machado – Faculdade Anhanguera de Brasília
Profª Drª Elane Schwinden Prudêncio – Universidade Federal de Santa Catarina
Profª Drª Eysler Gonçalves Maia Brasil – Universidade da Integração Internacional da Lusofonia Afro-Brasileira
Prof. Dr. Ferlando Lima Santos – Universidade Federal do Recôncavo da Bahia
Prof. Dr. Fernando Mendes – Instituto Politécnico de Coimbra – Escola Superior de Saúde de Coimbra
Profª Drª Gabriela Vieira do Amaral – Universidade de Vassouras
Prof. Dr. Gianfábio Pimentel Franco – Universidade Federal de Santa Maria
Prof. Dr. Helio Franklin Rodrigues de Almeida – Universidade Federal de Rondônia
Profª Drª Iara Lúcia Tescarollo – Universidade São Francisco
Prof. Dr. Igor Luiz Vieira de Lima Santos – Universidade Federal de Campina Grande
Prof. Dr. Jefferson Thiago Souza – Universidade Estadual do Ceará
Prof. Dr. Jesus Rodrigues Lemos – Universidade Federal do Piauí
Prof. Dr. Jônatas de França Barros – Universidade Federal do Rio Grande do Norte
Prof. Dr. José Max Barbosa de Oliveira Junior – Universidade Federal do Oeste do Pará
Prof. Dr. Luís Paulo Souza e Souza – Universidade Federal do Amazonas
Profª Drª Magnólia de Araújo Campos – Universidade Federal de Campina Grande
Prof. Dr. Marcus Fernando da Silva Praxedes – Universidade Federal do Recôncavo da Bahia
Profª Drª Maria Tatiane Gonçalves Sá – Universidade do Estado do Pará
Profª Drª Mylena Andréa Oliveira Torres – Universidade Ceuma
Profª Drª Natiéli Piovesan – Instituto Federacl do Rio Grande do Norte
Prof. Dr. Paulo Inada – Universidade Estadual de Maringá
Prof. Dr. Rafael Henrique Silva – Hospital Universitário da Universidade Federal da Grande Dourados
Profª Drª Regiane Luz Carvalho – Centro Universitário das Faculdades Associadas de Ensino
Profª Drª Renata Mendes de Freitas – Universidade Federal de Juiz de Fora
Profª Drª Vanessa Lima Gonçalves – Universidade Estadual de Ponta Grossa
Profª Drª Vanessa Bordin Viera – Universidade Federal de Campina Grande

Ciências Exatas e da Terra e Engenharias
Prof. Dr. Adélio Alcino Sampaio Castro Machado – Universidade do Porto
Prof. Dr. Carlos Eduardo Sanches de Andrade – Universidade Federal de Goiás
Profª Drª Carmen Lúcia Voigt – Universidade Norte do Paraná
Prof. Dr. Cleiseano Emanuel da Silva Paniagua – Instituto Federal de Educação, Ciência e Tecnologia de Goiás
Prof. Dr. Douglas Gonçalves da Silva – Universidade Estadual do Sudoeste da Bahia

Prof. Dr. Eloi Rufato Junior – Universidade Tecnológica Federal do Paraná
Profª Drª Érica de Melo Azevedo – Instituto Federal do Rio de Janeiro
Prof. Dr. Fabrício Menezes Ramos – Instituto Federal do Pará
Profª Dra. Jéssica Verger Nardeli – Universidade Estadual Paulista Júlio de Mesquita Filho
Prof. Dr. Juliano Carlo Rufino de Freitas – Universidade Federal de Campina Grande
Profª Drª Luciana do Nascimento Mendes – Instituto Federal de Educação, Ciência e Tecnologia do Rio Grande do Norte
Prof. Dr. Marcelo Marques – Universidade Estadual de Maringá
Prof. Dr. Marco Aurélio Kistemann Junior – Universidade Federal de Juiz de Fora
Profª Drª Neiva Maria de Almeida – Universidade Federal da Paraíba
Profª Drª Natiéli Piovesan – Instituto Federal do Rio Grande do Norte
Profª Drª Priscila Tessmer Scaglioni – Universidade Federal de Pelotas
Prof. Dr. Takeshy Tachizawa – Faculdade de Campo Limpo Paulista

Linguística, Letras e Artes

Profª Drª Adriana Demite Stephani – Universidade Federal do Tocantins
Profª Drª Angeli Rose do Nascimento – Universidade Federal do Estado do Rio de Janeiro
Profª Drª Carolina Fernandes da Silva Mandaji – Universidade Tecnológica Federal do Paraná
Profª Drª Denise Rocha – Universidade Federal do Ceará
Prof. Dr. Fabiano Tadeu Grazioli – Universidade Regional Integrada do Alto Uruguai e das Missões
Prof. Dr. Gilmei Fleck – Universidade Estadual do Oeste do Paraná
Profª Drª Keyla Christina Almeida Portela – Instituto Federal de Educação, Ciência e Tecnologia do Paraná
Profª Drª Miranilde Oliveira Neves – Instituto de Educação, Ciência e Tecnologia do Pará
Profª Drª Sandra Regina Gardacho Pietrobon – Universidade Estadual do Centro-Oeste
Profª Drª Sheila Marta Carregosa Rocha – Universidade do Estado da Bahia

Conselho Técnico Científico

Prof. Me. Abrãao Carvalho Nogueira – Universidade Federal do Espírito Santo
Prof. Me. Adalberto Zorzo – Centro Estadual de Educação Tecnológica Paula Souza
Prof. Dr. Adaylson Wagner Sousa de Vasconcelos – Ordem dos Advogados do Brasil/Seccional Paraíba
Prof. Dr. Adilson Tadeu Basquerote Silva – Universidade para o Desenvolvimento do Alto Vale do Itajaí
Prof. Dr. Alex Luis dos Santos – Universidade Federal de Minas Gerais
Prof. Me. Alexsandro Teixeira Ribeiro – Centro Universitário Internacional
Profª Ma. Aline Ferreira Antunes – Universidade Federal de Goiás
Prof. Me. André Flávio Gonçalves Silva – Universidade Federal do Maranhão
Profª Ma. Andréa Cristina Marques de Araújo – Universidade Fernando Pessoa
Profª Drª Andreza Lopes – Instituto de Pesquisa e Desenvolvimento Acadêmico
Profª Drª Andrezza Miguel da Silva – Faculdade da Amazônia
Profª Ma. Anelisa Mota Gregoleti – Universidade Estadual de Maringá
Profª Ma. Anne Karynne da Silva Barbosa – Universidade Federal do Maranhão
Prof. Dr. Antonio Hot Pereira de Faria – Polícia Militar de Minas Gerais
Prof. Me. Armando Dias Duarte – Universidade Federal de Pernambuco
Profª Ma. Bianca Camargo Martins – UniCesumar

Profª Ma. Carolina Shimomura Nanya – Universidade Federal de São Carlos
Prof. Me. Carlos Antônio dos Santos – Universidade Federal Rural do Rio de Janeiro
Prof. Me. Christopher Smith Bignardi Neves – Universidade Federal do Paraná
Prof. Ma. Cláudia de Araújo Marques – Faculdade de Música do Espírito Santo
Profª Drª Cláudia Taís Siqueira Cagliari – Centro Universitário Dinâmica das Cataratas
Prof. Me. Clécio Danilo Dias da Silva – Universidade Federal do Rio Grande do Norte
Prof. Me. Daniel da Silva Miranda – Universidade Federal do Pará
Profª Ma. Daniela da Silva Rodrigues – Universidade de Brasília
Profª Ma. Daniela Remião de Macedo – Universidade de Lisboa
Profª Ma. Dayane de Melo Barros – Universidade Federal de Pernambuco
Prof. Me. Douglas Santos Mezacas – Universidade Estadual de Goiás
Prof. Me. Edevaldo de Castro Monteiro – Embrapa Agrobiologia
Prof. Me. Eduardo Gomes de Oliveira – Faculdades Unificadas Doctum de Cataguases
Prof. Me. Eduardo Henrique Ferreira – Faculdade Pitágoras de Londrina
Prof. Dr. Edwaldo Costa – Marinha do Brasil
Prof. Me. Eliel Constantino da Silva – Universidade Estadual Paulista Júlio de Mesquita
Prof. Me. Ernane Rosa Martins – Instituto Federal de Educação, Ciência e Tecnologia de Goiás
Prof. Me. Euvaldo de Sousa Costa Junior – Prefeitura Municipal de São João do Piauí
Prof. Dr. Everaldo dos Santos Mendes – Instituto Edith Theresa Hedwing Stein
Prof. Me. Ezequiel Martins Ferreira – Universidade Federal de Goiás
Profª Ma. Fabiana Coelho Couto Rocha Corrêa – Centro Universitário Estácio Juiz de Fora
Prof. Me. Fabiano Eloy Atílio Batista – Universidade Federal de Viçosa
Prof. Me. Felipe da Costa Negrão – Universidade Federal do Amazonas
Prof. Me. Francisco Odécio Sales – Instituto Federal do Ceará
Profª Drª Germana Ponce de Leon Ramírez – Centro Universitário Adventista de São Paulo
Prof. Me. Gevair Campos – Instituto Mineiro de Agropecuária
Prof. Me. Givanildo de Oliveira Santos – Secretaria da Educação de Goiás
Prof. Dr. Guilherme Renato Gomes – Universidade Norte do Paraná
Prof. Me. Gustavo Krahl – Universidade do Oeste de Santa Catarina
Prof. Me. Helton Rangel Coutinho Junior – Tribunal de Justiça do Estado do Rio de Janeiro
Profª Ma. Isabelle Cerqueira Sousa – Universidade de Fortaleza
Profª Ma. Jaqueline Oliveira Rezende – Universidade Federal de Uberlândia
Prof. Me. Javier Antonio Albornoz – University of Miami and Miami Dade College
Prof. Me. Jhonatan da Silva Lima – Universidade Federal do Pará
Prof. Dr. José Carlos da Silva Mendes – Instituto de Psicologia Cognitiva, Desenvolvimento Humano e Social
Prof. Me. Jose Elyton Batista dos Santos – Universidade Federal de Sergipe
Prof. Me. José Luiz Leonardo de Araujo Pimenta – Instituto Nacional de Investigación Agropecuaria Uruguay
Prof. Me. José Messias Ribeiro Júnior – Instituto Federal de Educação Tecnológica de Pernambuco
Profª Drª Juliana Santana de Curcio – Universidade Federal de Goiás
Profª Ma. Juliana Thaisa Rodrigues Pacheco – Universidade Estadual de Ponta Grossa
Profª Drª Kamilly Souza do Vale – Núcleo de Pesquisas Fenomenológicas/UFPA
Prof. Dr. Kárpio Márcio de Siqueira – Universidade do Estado da Bahia
Profª Drª Karina de Araújo Dias – Prefeitura Municipal de Florianópolis
Prof. Dr. Lázaro Castro Silva Nascimento – Laboratório de Fenomenologia & Subjetividade/UFPR

Prof. Me. Leonardo Tullio – Universidade Estadual de Ponta Grossa
Profª Ma. Lilian Coelho de Freitas – Instituto Federal do Pará
Profª Ma. Liliani Aparecida Sereno Fontes de Medeiros – Consórcio CEDERJ
Profª Drª Lívia do Carmo Silva – Universidade Federal de Goiás
Prof. Dr. Lucio Marques Vieira Souza – Secretaria de Estado da Educação, do Esporte e da Cultura de Sergipe
Prof. Dr. Luan Vinicius Bernardelli – Universidade Estadual do Paraná
Profª Ma. Luana Ferreira dos Santos – Universidade Estadual de Santa Cruz
Profª Ma. Luana Vieira Toledo – Universidade Federal de Viçosa
Prof. Me. Luis Henrique Almeida Castro – Universidade Federal da Grande Dourados
Profª Ma. Luma Sarai de Oliveira – Universidade Estadual de Campinas
Prof. Dr. Michel da Costa – Universidade Metropolitana de Santos
Prof. Me. Marcelo da Fonseca Ferreira da Silva – Governo do Estado do Espírito Santo
Prof. Dr. Marcelo Máximo Purificação – Fundação Integrada Municipal de Ensino Superior
Prof. Me. Marcos Aurelio Alves e Silva – Instituto Federal de Educação, Ciência e Tecnologia de São Paulo
Profª Ma. Maria Elanny Damasceno Silva – Universidade Federal do Ceará
Profª Ma. Marileila Marques Toledo – Universidade Federal dos Vales do Jequitinhonha e Mucuri
Prof. Me. Pedro Panhoca da Silva – Universidade Presbiteriana Mackenzie
Profª Drª Poliana Arruda Fajardo – Universidade Federal de São Carlos
Prof. Me. Ricardo Sérgio da Silva – Universidade Federal de Pernambuco
Prof. Me. Renato Faria da Gama – Instituto Gama – Medicina Personalizada e Integrativa
Profª Ma. Renata Luciane Polsaque Young Blood – UniSecal
Prof. Me. Robson Lucas Soares da Silva – Universidade Federal da Paraíba
Prof. Me. Sebastião André Barbosa Junior – Universidade Federal Rural de Pernambuco
Profª Ma. Silene Ribeiro Miranda Barbosa – Consultoria Brasileira de Ensino, Pesquisa e Extensão
Profª Ma. Solange Aparecida de Souza Monteiro – Instituto Federal de São Paulo
Profª Ma. Taiane Aparecida Ribeiro Nepomoceno – Universidade Estadual do Oeste do Paraná
Prof. Me. Tallys Newton Fernandes de Matos – Faculdade Regional Jaguaribana
Profª Ma. Thatianny Jasmine Castro Martins de Carvalho – Universidade Federal do Piauí
Prof. Me. Tiago Silvio Dedoné – Colégio ECEL Positivo
Prof. Dr. Welleson Feitosa Gazel – Universidade Paulista

Atena
Editora
Ano 2021

Engenharia elétrica: comunicação integrada no universo da energia

Editora Chefe: Profª Drª Antonella Carvalho de Oliveira
Bibliotecária: Janaina Ramos
Diagramação: Camila Alves de Cremo
Correção: Mariane Aparecida Freitas
Edição de Arte: Luiza Alves Batista
Revisão: Os Autores
Organizadores: João Dallamuta
Henrique Ajuz Holzmann

Dados Internacionais de Catalogação na Publicação (CIP)

E57 Engenharia elétrica: comunicação integrada no universo da energia / Organizadores João Dallamuta, Henrique Ajuz Holzmann. – Ponta Grossa - PR: Atena, 2021.

Formato: PDF
Requisitos de sistema: Adobe Acrobat Reader
Modo de acesso: World Wide Web
Inclui bibliografia
ISBN 978-65-5706-837-3
DOI 10.22533/at.ed.373212302

1. Energia. 2. Engenharia. I. Dallamuta, João (Organizador). II. Holzmann, Henrique Ajuz (Organizador). III. Título.

CDD 621.1

Elaborado por Bibliotecária Janaina Ramos – CRB-8/9166

Atena Editora
Ponta Grossa – Paraná – Brasil
Telefone: +55 (42) 3323-5493
www.atenaeditora.com.br
contato@atenaeditora.com.br

Atena Editora
Ano 2021

Ciências Exatas e da Terra e Engenharias

Ciências Exatas e da Terra e Engenharias

DECLARAÇÃO DOS AUTORES

Os autores desta obra: 1. Atestam não possuir qualquer interesse comercial que constitua um conflito de interesses em relação ao artigo científico publicado; 2. Declaram que participaram ativamente da construção dos respectivos manuscritos, preferencialmente na: a) Concepção do estudo, e/ou aquisição de dados, e/ou análise e interpretação de dados; b) Elaboração do artigo ou revisão com vistas a tornar o material intelectualmente relevante; c) Aprovação final do manuscrito para submissão.; 3. Certificam que os artigos científicos publicados estão completamente isentos de dados e/ou resultados fraudulentos; 4. Confirmam a citação e a referência correta de todos os dados e de interpretações de dados de outras pesquisas; 5. Reconhecem terem informado todas as fontes de financiamento recebidas para a consecução da pesquisa.

Atena
Editora
Ano 2021

APRESENTAÇÃO

A engenharia elétrica tornou-se uma profissão há cerca de 130 anos, com o início da distribuição de eletricidade em caráter comercial e com a difusão acelerada do telégrafo em escala global no final do século XIX.

Na primeira metade do século XX a difusão da telefonia e da radiodifusão além do crescimento vigoroso dos sistemas elétricos de produção, transmissão e distribuição de eletricidade, deu os contornos definitivos para a carreira de engenheiro eletricista que na segunda metade do século, com a difusão dos semicondutores e da computação gerou variações de ênfase de formação como engenheiros eletrônicos, de telecomunicações, de controle e automação ou de computação.

Não há padrões de desempenho em engenharia elétrica e da computação que sejam duradouros. Desde que Gordon E. Moore fez a sua clássica profecia tecnológica, em meados dos anos 60, a qual o número de transistores em um chip dobraria a cada 18 meses - padrão este válido até hoje – muita coisa mudou. Permanece porem a certeza de que não há tecnologia na neste campo do conhecimento que não possa ser substituída a qualquer momento por uma nova, oriunda de pesquisa científica nesta área.

Produzir conhecimento em engenharia elétrica é, portanto, atuar em fronteiras de padrões e técnicas de engenharia. Também se trata de uma área de conhecimento com uma grande amplitude de subáreas e especializações, algo desafiador para pesquisadores e engenheiros.

Neste livro temos uma diversidade de temas nas áreas níveis de profundidade e abordagens de pesquisa, envolvendo aspectos técnicos e científicos. Aos autores e editores, agradecemos pela confiança e espírito de parceria.

Boa leitura

João Dallamuta
Henrique Ajuz Holzmann

SUMÁRIO

CAPÍTULO 2

ASSESSMENT OF THE IMPACT OF GROUNDING SYSTEMS MODELING ON THE LIGHTNING PERFORMANCE OF TRANSMISSION LINES

Data de aceite: 22/02/2021
Data de submissão: 29/01/2021

Felipe Vasconcellos
Department of Electrical and Computer Engineering of Federal University of Bahia (UFBA)
http://lattes.cnpq.br/0508094462424211

Rafael Alípio
Department of Electrical Engineering of Federal Center of Technological Education of Minas Gerais (CEFET-MG)
http://lattes.cnpq.br/6715701375569983

Fernando Moreira
Department of Electrical and Computer Engineering of Federal University of Bahia (UFBA)
http://lattes.cnpq.br/8068628216980918

ABSTRACT: This paper investigates the impact of grounding systems modeling on the lightning performance of overhead transmission lines. The developed overvoltages though the insulator string and the backflashover rates of a Brazilian 138-kV transmission line are estimated, while the tower-footing grounding system is represented by three different models, namely: i) a static model, consisting of a lumped resistance with value equal to the low-frequency grounding resistance, ii) a full-wave wideband model (as known as HEM – Hybrid Electromagnetic Model), and iii) a pi-cascade wideband model. Taking as reference the results, it is shown that the static model can lead to errors and incorrect predictions of insulation breakdown. Concerning to the wideband models, HEM unquestionably produces the most precise results, but based on the results of this work, it is shown that the pi-cascade model is relatively accurate, with the advantage of requiring much less computational effort and simulation time, which makes it attractive for applications where this feature is important, such as probabilistic analysis (based on numerous simulations) and/or Engineering applications.

KEYWORDS: Transmission lines; grounding systems, frequency-dependent soil electrical parameters, lightning performance, backflashover.

AVALIAÇÃO DO IMPACTO DA MODELAGEM DOS SISTEMAS DE ATERRAMENTO SOBRE O DESEMPENHO DAS LINHAS DE TRANSMISSÃO FRENTE A DESCARGAS ATMOSFÉRICAS

RESUMO: Este artigo investiga o impacto da modelagem de sistemas de aterramento no desempenho de linhas de transmissão frente a descargas atmosféricas. As sobretensões desenvolvidas através da cadeia isolante e as taxas de desligamento por backflashover de uma linha de transmissão de 138 kV brasileira são estimadas, enquanto o sistema de aterramento do pé de torre é representado por três modelos diferentes, a saber: i) um modelo estático, consistindo de uma resistência de concentrada com valor igual à resistência de aterramento de baixa freqüência, ii) um modelo de banda larga de onda completa (como conhecido como HEM - Hybrid Electromagnetic Model), e iii) um modelo de banda larga em cascata de pi. Tomando como referência os resultados, é mostrado que o modelo estático pode levar a erros e previsões incorretas de ruptura do isolamento. Com relação aos modelos de banda larga, o HEM produz inquestionavelmente os resultados mais precisos, mas com base nos resultados deste trabalho, mostra-se que o modelo de cascata de pi é relativamente preciso, com a vantagem de exigir muito menos esforço computacional e tempo de simulação, o que o torna atrativo para aplicações onde esta característica é importante, tais como análises probabilísticas (baseada em numerosas simulações) e/ou aplicações de Engenharia.

PALAVRAS-CHAVE: Linhas de transmissão, sistemas de aterramento, parâmetros elétricos de solo dependents da frequência, performance frente a descargas atmosféricas, backflashover.

1 I INTRODUCTION

Direct lightning strikes to the transmission line towers or to the shielding wires can result in severe overvoltages across insulators leading to line outages. Backflashover events are mostly responsible for lightning-related outages of lines below 500 kV installed in regions within soil resistivity from moderate to high [1, 2].

Inside the scientific community, the discussion concerning the most effective approach for modelling grounding systems remains an open issue and electromagnetic field theory (EMF) or transmission line models (with lumped or distributed parameters) are yet both popularly used. Undoubtedly, EMF theory models produces the most precise results, while transmission line models are strongly constrained by low frequency quasi-static approximations. Otherwise, EMF models implementation could become complicated and time consuming when grounding systems have complex and/or realistic geometry. On the other hand, the transmission line models, when carefully applied, allows an easier implementation on commercially (or even free) available software for electromagnetic transient analysis. The need to use adequate models for the frequency content of the studied phenomena is an important factor that should be considered for simulating electromagnetic transients [3].

Traditionally, the lightning performance of transmission lines is evaluated using the broadly accepted time-domain electromagnetic transient tools (ATP-EMTP, EMTP-RV, and PSCAD), due to their effectiveness to handle with complex networks and diversified system apparatus [4, 5]. Nevertheless, there is no model that consider the frequency-dependent behavior of the grounding system inherent to these time-domain tools, and consequently, it is often modelled as a simple lumped resistance [6]. This simplification overestimates results which do not are consistent with values found experimentally [7][8][9]. A possibility to improve these results is to determine the grounding system response in the frequency domain for the frequency range of the transient study and then use a rational approximation which reproduces the frequency response of the grounding systems through a synthesized R-L-C equivalent circuit [10].

Additionally, the soil permittivity and conductivity highly vary along the typical frequency range of lightning currents, being this effect not included in the aforementioned time-domain tools [11]. Recent works show that such frequency-dependent behavior of soil parameters greatly impacts the lightning performance of grounding systems [8, 12, 13].

Within this context, this work aims to investigate the impact of grounding systems modeling on the lighting performance of overhead transmission lines, and to evaluate the applicability of each representation. The paper is organized as follows: section 2 describes the methodology and system description; the modeling guidelines are presented in section 3; simulation results and analysis are shown in section 4; and the main conclusions on this work are related in section 5.

2 I METHODOLOGY AND SYSTEM DESCRIPTION

To evaluate the influence of grounding systems modeling on the lightning performance of transmission lines in areas with high soil resistivity, a 138-kV Brazilian transmission line is considered (CFO = 650 kV).

The incidence of lightning strikes to the top of a transmission tower is simulated. Two adjacent towers (identical to the stricken one) are included in the simulations to consider the effect of wave propagation along the line conductors and also the reflections from the adjacent towers and its grounding systems. Two spans of 400 m long each are considered at each side of the striking point. The lines after each adjacent tower are sufficiently long to avoid reflections.

Figure 1 illustrates the typical tower silhouette, designed with one ACSR conductor per phase (LINNET) and one 3/8’’ EHS shield wire. The coordinates of the line cables (in meters) are indicated in the same figure (values within parenthesis are midspan heights).

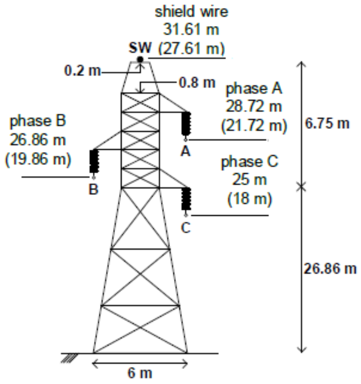

Fig. 1. Typical tower silhouette.

The typical grounding system design of the transmission line towers is depicted in Fig. 2. It contains four counterpoise cables of 7 mm radius and buried 0.5 m deep in the soil.

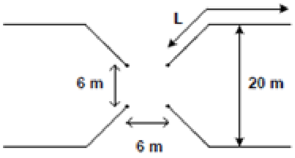

Fig. 2. Typical arrangement of tower's grounding systems.

The length (L) of the counterpoise cables is set according to the low-frequency soil resistivity ρ_0, as indicated in Table I. It is worth mentioning that the length of the cable is established by the effective length for first strokes and also considering local engineering practices.

ρ (Ω.m)	1,000	3,000	5,000	10,000
L (m)	40	60	80	130

Table I - Counterpoise cable length according to soil resistivity

The Disruptive Effect (DE) Method is applied to check the occurrence of insulation breakdown. The conception of the DE method is based on the idea that there exists a base disruptive effect (DE_B) for each specific insulation configuration. If a nonstandard surge exceeds this base DE_B, it is considered that flashover occurs. On the other hand, if the surge is less than this base DE_B, it is assumed that no flashover occurs [14].

The general equation for the disruptive effect is

$$DE = \int_{t_0}^{t} [e(t) - V_0]^k \, dt \qquad (1)$$

where e(t) is the voltage across the insulator. For a typical 138-kV line, the constants of the DE method are: $DE_B = 1.1506(CFO)^k$; $k = 1.36$; $V_0/CFO = 0.770$ [14].

The simulations presented in this work were performed using ATP/EMTP. The advantage of using this type of tool is its low computational effort associated with adequate precision, especially when it comes to engineering applications [15].

The modeling guidelines of the simulated power system is then briefly described.

3 I MODELING GUIDELINES

3.1 Lightning current waveform

A proper evaluation of lightning effects on power systems relies upon, among other factors, on an appropriate representation of the lightning current waveform since the quality of the simulation results depends on the representativity of the assumed lightning current waves [16].

According to [17], the first stroke currents are characterized by a pronounced concavity at the front and by the occurrence of multiple peaks, being the second peak usually the highest one, and the maximum steepness occurring near the first peak according to measurements of instrumented towers, such as those presented in [18,19].

Considering the previous aspects, the simulations were performed considering some brazilian conditions, as the current waveform depicted in fig. 3, that approximately reproduces the main median parameters of first strokes measured at morro do cachimbo station. As detailed in [20], the waveform of fig. 3 is obtained by a sum of Heidler functions.

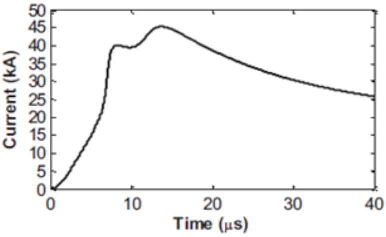

Fig. 3. Representative lightning current waveform of first strokes measured at Morro do Cachimbo Station.

3.2 Phase cables and shield wire

The phase cables and shield wire are modeled using the lcc tool of atp [9], that includes the well-known line constants and cable constants routines. In lcc, the cables and shield wire positions are set in accordance with the tower silhouette, as shown in fig. 1, and the frequency-dependent line model JMARTI is used [21].

3.3 Transmission line tower

the transmission tower is modeled as a lossless single-phase transmission line, and its surge impedance is calculated using the revised Jordan's formula, that was extended in [22] to consider vertical multiconductor systems. Assuming that the tower can be represented by n vertical conductors that are connected at the same current injection point, it is possible to model the whole multiconductor system as a single transmission line with equivalent surge impedance Z_{eq} given by [22]

$$Z_{eq} = \frac{V}{I} = \frac{Z + Z_{12} + \ldots + Z_{1n}}{n} \tag{2}$$

where

$$Z = 60\left[ln\frac{4h}{r} - 1\right] \tag{3}$$

and

$$Z_{ij} = 60ln\frac{2h + \sqrt{4h^2 + d_{ij}{}^2}}{d_{ij}} + 30\frac{d}{h} - 60\sqrt{\frac{1 + d_{ij}{}^2}{4h^2}} \tag{4}$$

In (2) and (3), *h* is the height of the conductor, *r* is the conductor radius, and d_{ij} corresponds to the distance between the center of the conductors *i* and *j*. Particularly, the tower of Fig. 1 was sectioned in four segments, each one represented by four vertical conductors. The lower part of the tower was represented as a cascade of three transmission lines (two of 9 m and one of 8.86 m), while its upper part was represented as a single 6.75-m long transmission line. This was made to consider the variation of the cross section of the tower with position, which changes the mutual surge impedance as a function of height. The equivalent impedance of each tower section was computed using (1), (2) and (3), considering the average distances between tower conductors and assuming r = 6.5 cm. The propagation speed of the surge wave was assumed to be 80% of speed of light, as in [22]. The final tower model is illustrated in Fig. 4.

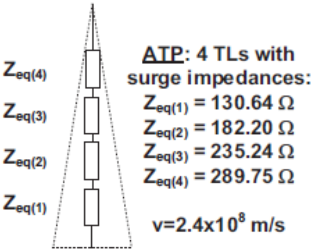

Fig. 4. Transmission tower representation.

3.4 Tower-footing grounding

The tower-footing grounding system is represented by three different models:

I. **Static model (STM)**: a simple resistor of value equal to the low-frequency grounding resistance of the tower-footing grounding system is connected to the base of the transmission towers.

II. **Full-wave** and **iii) pi-cascade (PIM) wideband model:** an equivalent circuit that contemplates the wideband response of the tower-footing grounding system is connected to the base of the transmission towers.

In ii) the tower-footing ground harmonic impedance Z(*jω*) is computed applying the Hybrid Electromagnetic Model (HEM) [23], based on the Full-Wave Maxwell Equations and validated from experimental results. This model is acknowleged as a benchmark for its accuracy.

In iii) the tower-footing ground harmonic impedance Z(*jω*) is computed applying an adapted pi-cascade model [24], based on transmission line theory. An adaptation of the original model was made, in which the internal resistance of the cable was neglected, as it is insignificant in relation to the grounding impedance, as the counterpoise cables are manufactured using conductive material.

Grounding conductors are characterised by a series inductance *L*, a shunt conductance *G* and a shunt capacitance C. They can be modelled as series connected pi-equivalent circuits with lumped R-L-C elements, based on the well-known Sunde's expressions, where each pi-circuit corresponds to a small conductor segment (Fig.5) [24].

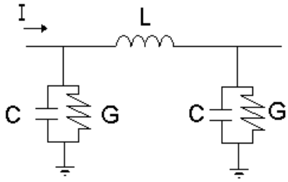

Fig. 5. Pi-equivalent circuit. Adapted from [24].

The frequency-dependent behaviour of the electrical soil parameters was included considering the rigorous causal model proposed by Alipio and Visacro [7], which is based on a large number of soil parameter measurements performed in field conditions [25]-[26]. After the computation of the harmonic impedance Z(jω), a pole-residue model, given by eq. (4), of the associated admittance Y(jω) = 1/ Z(jω) is acquired using the Vector Fitting (VF) method [10]. In the end, from the acquired passive pole-residue model of the grounding admittance, it is possible to synthesize an electrical circuit, which can be included directly in time-domain simulations.

$$Y(s = j\omega) \cong Y_{fit}(s = j\omega) = \sum_{m=1}^{N} \frac{r_m}{s - a_m} + d + se \qquad (5)$$

In (4), a_m and r_m, respectively, express the poles and residues of the pole-residue approximation I_{fit}, while d and e are constant real values, and N is the number of poles (order of the pole-residue model). To achieve stable time-domain simulations, the passivity is enforced by perturbation of the model parameters [27]. It is relevant to mention that both pole-residue model and electrical circuits were achieved applying the public domain calculation package for a rational approximation of frequency-dependent admittance matrices available in [28].

4 I RESULTS AND ANALYSIS

To assess the impact of the grounding systems modeling in terms of the lightning performance of the transmission lines, the following cases were simulated: i) static model (STM); ii) full-wave wideband model (HEM); iii) pi-cascade wideband model (PIM). Four values of soil resistivity were considered (1,000; 3,000; 5,000; and 10,000 Ω.m), and the corresponding lengths of counterpoise are indicated in Table I.

The developed overvoltages waves and peak values are presented in subsection 4.1. The outage rates of the lines considering uniform and non-uniform distribution of soil resistivities along the transmission line are shown in subsection 4.2.

4.1 Developed overvoltages

The overvoltages developed through the upper insulator string (phase A) of the 138 kV line due to the incidence of a lightning strike at the top of the tower are shown in Fig. 6. It was decided to present only the graphs and values corresponding to phase A because it was the phase that presented the highest overvoltage values in all the cases studied, thus being the most relevant for the lightning performance and outage rates evaluation, besides providing a less polluted graphical representation.

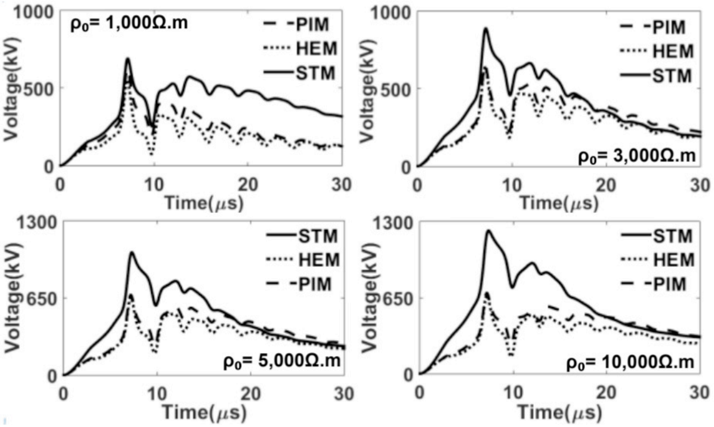

Fig. 6. Resultant Overvoltage waves of phase A (upper) for soil resistivity values from 1,000Ω.m to 10,000Ω.m.

ρ	L	STM	HEM	PIM	Δ	∂
1,000	40	621	554	572	12.1%	3.2%
3,000	60	890	650	660	36.9%	1.5%
5,000	80	1035	677	682	52.9%	0.7%
10,000	130	1224	691	693	77.1%	0.3%

Table II – Resultant Overvoltages of Phase A for soil resistivity values from 1,000Ω.m to 10,000Ω.m considering the three grounding systems models.

As expected, from the voltage waves of Fig.6 and the numerical results from Table II, applying the static model (STM) leads to superior overvoltage levels to those determined considering both wideband models. These results are computed in the column Δ and varies from 12.1% to 77.1%, when compared to the benchmark (HEM). Such differences may lead to the incorrect prediction of insulation breakdown when the grounding is represented by a simple resistor with low-frequency resistance value, as will be seen in the next subsection.

In contrast, when comparing the pi-cascade model with HEM, the differences, shown in column ∂, were between 0.3% and 3.2%, which demonstrates a comparable level of accuracy. It can be seen that there is a direct relationship between the soil resistivity, the counterpoise cable's length and the model precision, and that it becomes more precise as the previous parameters increase.

4.2 Backflashover rates

In order to estimate the backflashover rate of a transmission line, it is first necessary to calculate the critical current that would lead to the insulation breakdown. For a given set of line conditions and with the current waveform defined, it is possible to easily identify the critical peak current (I_c) that leads to the insulation breakdown. With the current waveform maintained, it is sufficient to increase its peak value until the corresponding overvoltage amplitude reaches the breaking condition. The DE method was applied to the overvoltage waves from section 4.1 to determine the peak value of the critical current I_c, with the aforementioned three representations of the grounding systems.

The calculated I_c values are shown in Table III, together with the occurrence probability of peak currents above I_c ($P\,[I \geq I_c]$). They are determined from the cumulative probability distribution of peak currents for first return strokes measured at the Morro do Cachimbo station - MG [19], which is approximately

$$P_I = 1/[1 + (I/45{,}3)^{3{,}9}] \tag{6}$$

According to the results of the Table III, it can be seen that the static model leads to incorrect estimates, although conservative, of the critical currents, and it becomes more prominent for soils of higher resistivity. Thus, the probabilities of occurrence of peak currents above I_c are increased, as indicated on the Δ column in Table III, and varies from 74.5% to

137.2%, when compared to the HEM. It is because HEM (and PIM) incorporate the frequency-dependent behavior of the grounding systems and the soil electrical parameters. Among other aspects, such effects lead to an improvement of impulsive grounding performance. In order to simplify, for the analyzed cases in which the length of the counterpoise cables does not exceed the effective length, the front of the lightning current wave “sees” an impulsive impedance that is lower than the low-frequency resistance. The differences among the results determined using the static model and the wideband models become more accentuated as the resistivity of the soil increases because the impact of the frequency-dependent effects are much more significant the greater the resistivity of the soil becomes.

Despite the increase, the differences between the two wideband models still remain relatively close, ranging from 4.9% to 13.2%, as seen in column ∂ of the Table III.

ρ_0 (Ω·m)	L (m)	STM		HEM		PIM		Δ	∂
		I_C (kA)	$I_p > I_C$ (%)	I_C (kA)	$I_p > I_C$ (%)	I_C (kA)	$I_p > I_C$ (%)		
1,000	40	77	11.2%	90	6.4%	87	7.3%	74.5%	13.2%
3,000	60	46	48.5%	62	22.7%	60	25.1%	113.5%	10.3%
5,000	80	38	66.5%	55	31.9%	54	35.2%	108.2%	10.1%
10,000	130	32	79.5%	54	33.5%	53	35.2%	137.2%	4.9%

Table III – Critical currents of the transmission lines for soil resistivity values from 1,000Ω.m to 10,000Ω.m and their probabilities.

From the probability of breakdown occurrence shown in Table III, the estimated backflashover rates of the transmission line were calculated following a similar procedure indicated by Anderson [29]. The proposed methodology requires certain preliminary information, such as the geometry of the tower, the ground flash density (N_g), and the distribution of soil resistivity along the transmission line path. The value of $N_g = 10$ was considered, as it is the average value found in the state of Minas Gerais [30], where the Morro do Cachimbo Station is also located.

Table IV summarizes the results of backflashover rate estimates considering the three studied models. The analysis considers nine different soil resistivity distributions along the line: four uniform distributions (ρ_0 from 1,000 to 10,000 Ω.m) and three non-uniform distributions, in these cases representing varying soil conditions along the line, thus being more realistic.

Hypotheses for the distribution of ρ along the transmission line (%)				Number of Backflashovers/100km/year				
1,000 (Ω.m)	3,000 (Ω.m)	5,000 (Ω.m)	10,000 (Ω.m)	STM	HEM	PIM	Δ	∂
100%	0%	0%	0%	4.1	2.4	2.7	70.8%	12.5%
0%	100%	0%	0%	17.8	8.3	9.2	114.5%	10.8%
0%	0%	100%	0%	24.3	11.7	12.9	107.7%	10.3%
0%	0%	0%	100%	29.1	12.3	12.9	136.6%	4.9%
50%	30%	20%	0%	12.3	6.0	6.7	103.2%	10.9%
25%	35%	30%	10%	17.5	8.2	9.1	111.7%	9.8%
0%	40%	30%	30%	23.1	10.5	11.4	120.0%	8.6%
0%	20%	40%	40%	24.9	11.3	12.2	121.3%	8.0%
0%	0%	30%	70%	27.7	10.5	11.4	128.2%	6.4%

Table IV – Estimated backflashover rate of the transmission lines according to soil resistivity conditions along the line.

Consistent with the results presented before, the backflashover rates estimates when using the STM range from 4.1 to 29.1, resulting in a difference range from 70.8% to 136.6%. These results prove the importance of the rigorous representation of the line grounding system in this kind of study, at the risk of incurring in erroneous line protection strategies with a possible increase in the transmission line construction costs.

Finally, regarding to the wideband models, it is observed that the difference between PIM and HEM varies from 12.5% to 4.9%, however, for the proposed non-uniform distributions of soil resistivity (which are more realistic), these remain below 10% approximately, reaching 6.4%, and that this difference decreases as the soil resistivity and the length of the counterpoise cable increases.

In this work, it is not intended to question the accuracy of the HEM, on the contrary, after all, it was used as a benchmark. However, from the results presented, one can analyze the possibility of using it for certain conditions and applications, notably applications that need less computational effort and simulation time, such as probabilistic analysis (based on numerous simulations) and other Engineering applications simulating transmission lines with long counterpoise cables and highly resistive soils.

5 I CONCLUSIONS

The impact of grounding systems modeling on the lightning performance of transmission lines was assessed. To this aim, the grounding system was represented by three different models, namely: i) a static model, consisting of a lumped resistance with value equal to the low-frequency grounding resistance, ii) a full-wave wideband model, and iii) a pi-cascade wideband model. The frequency-dependent effect of the soil parameters was also included in ii) and iii).

The developed overvoltages were simulated using ATP/EMTP and the backflashover rates were computed in order to compare the lightning response of the transmission lines obtained from each modeling.

From the simulated cases, it is clear that using the static model, although conservative, causes overestimated results of overvoltage and backflashover rates to those determined using the most rigorous wideband models.

Finally, concerning to the wideband models, it is unquestionably that HEM produces the most accurate results, so much so that it has been used as a benchmark for the transmission line model. However, depending on the simulation conditions, the results are relatively close, and thus the possibility of using transmission line modeling in applications that present such conditions and that require low computational effort, such as probabilistic evaluations and/or other Engineering applications, is analyzed.

REFERENCES

[1] VISACRO, S., "Direct strokes to transmission lines: Considerations on the mechanisms of overvoltage formation and their influence on the lightning performance of lines," *J. Light. Res.*, vol. 1, pp. 60–68, 2007.

[2] VISACRO, S., SILVEIRA, F.H., and DE CONTI, A., "The use of underbuilt wires to improve the lightning performance of transmission lines," *IEEE Trans. Power Del.*, vol. 27, no. 1, pp. 205-213, Jan. 2012.

[3] CELLI, G., GHIANI, E. and PILO, F., "Behaviour of grounding systems: a quasi-static EMTP model and its validation," *2010 30th International Conference on Lightning Protection (ICLP)*, Cagliari, 2010, pp. 1-6, doi: 10.1109/ICLP.2010.7845954.

[4] AMETANI, A. and KAWAMURA, T., "A method of a lightning surge analysis recommended in Japan using EMTP", *IEEE Trans. Power Del.*, 20 (2005), No. 2, 867–875.

[5] TAKAMI, J., OKABE, S., and ZAIMA, E., "Study of lightning surge overvoltages at substations due to direct lightning strokes to phase conductors", *IEEE Trans. Power Delivery*, 25 (2010), No. 1, 425–433.

[6] SHESHYEKANI, K., AKBARI, M., TABEI, B., and KAZEMI, R., "Wideband modelling of large grounding systems to interface with electromagnetic transient solvers", *IEEE Trans. Power Delivery*, 29 (2014), No. 4, 1868–1876.

[7] ALIPIO, R. and VISACRO, S., "Modeling the frequency dependence of electrical parameters of soil," *IEEE Trans. Electromagn. Compat.*, vol. 56, no. 5, pp. 1163–1171, Oct. 2014.

[8] VISACRO, S. and SILVEIRA, F., "The impact of the frequency dependence of soil parameters on the lightning performance of transmission lines," *IEEE Trans. Electromagn. Compatibility*, vol. 57, no. 3, pp. 434–441, June 2015.

[9] ALIPIO, R. S., SCHROEDER, M. A. O., AFONSO, M. M., and OLIVEIRA, T. A. S., "Grounding modeling for high-frequency phenomena and comparison with experimental results" (in Portuguese), *Revista SBA Controle & Automação*, 2010.

[10] GUSTAVSEN, B. and SEMLYEN, A., “Rational approximation of frequency domain responses by vector fitting”, *IEEE Trans. Power Delivery*, 14 (1999), 1052–1061.

[11] ALIPIO, R. and VISACRO, S, “Time-domain analysis of frequency-dependent electrical parameters of soil”, *IEEE Trans. Electromagn. Compat*., 59 (2017), No. 3, 873–878.

[12] ALIPIO, R. and VISACRO, S., “Frequency dependence of soil parameters: effect on the lightning response of grounding electrodes”, *IEEE Trans. Electromagn. Compat.*, 55 (2013), No. 1, 132–139.

[13] ALIPIO, R. and VISACRO, S., “Impulse efficiency of grounding electrodes: effect of frequency dependent soil parameters”, *IEEE Trans. Power Delivery*, 29 (2014), No. 2, 716–723.

[14] HILEMAN, A. R., Insulation Coordination for Power Systems, 1st ed., CRC Press, 1999, pp.627–640.

[15] GERI, A. and VISACRO, S.F. “Grounding systems under surge conditions: comparison between a field model and a circuit model”, *Proc. of 26th ICLP*, Krakow, Poland, 2002.

[16] GUIMARÃES, G.C., CHAVES, M.L.R., BOAVENTURA, W.C., CAIXETA, D.A., TAMASHIRO, M.A., and RODRIGUES, A.R., “Lightning performance of transmission lines based upon real return-stroke current waveforms and statistical variation of characteristic parameters”, *Electr. Power Syst. Res.* (2016), http://dx.doi.org/10.1016/j.epsr.2016.12.003.

[17] VISACRO, S., “A representative curve for lightning current waveshape of first negative stroke”, *Geophysical Research Letters*, vol. 31, L07112, Apr. 2004.

[18] BERGER, K., ANDERSON, R. B., and KRONINGER, H., “Parameters of lightning flashes”, *Electra*, no. 80, pp. 223–237, 1975.

[19] VISACRO, S., SOARES, A., SCHROEDER, M. A. O., CHERCHIGLIA, L. C. L., and SOUSA, V. J., “Statistical analysis of lightning current parameters: measurements at Morro do Cachimbo station”, *Journal on Geophysical Research*, vol. 109, D01105, pp. 1–11, Jan. 2004.

[20] DE CONTI, A. and VISACRO, S., “Analytical representation of single- and double-peaked lightning current waveforms”, *IEEE Trans. Electromagnetic Compatibility*, vol. 49, no. 2, pp. 448–451, May 2007.

[21] MARTI, J. R., “Accurate modelling of frequency-dependent transmission lines in electromagnetic transient simulation”, *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 1, pp. 147–157, Jan. 1982.

[22] DE CONTI, A., VISACRO, S., SOARES, A., and SCHROEDER, M. A. O., “Revision, extension and validation of Jordan’s formula to calculate the surge impedance of vertical conductors”, *IEEE Trans. Electromagn. Compat.*, vol. 48, no. 3, pp. 530–536, Aug. 2006.

[23] VISACRO, S., SOARES JR, A., “HEM: a model for simulation of lightning related engineering problems” *IEEE Trans. Power Delivery*, vol. 20, no. 2, pp. 1026–1028, Apr. 2005.

[24] HATZIARGYRIOU, N. D. and LORENTZOU, M., “Grounding systems design using EMTP”, in *Proc. 23rd European EMTP Users Group Meeting*, Barcelona, Spain, November 9–11, 1997.

[25] VISACRO, S. and ALIPIO, R., “Frequency dependence of soil parameters: experimental results, predicting formula and influence on the lightning response of grounding electrodes”, *IEEE Trans. Power Del.*, vol. 27, no. 2, pp. 927–935, Apr. 2012.

[26] VISACRO, S. and ALIPIO, R., MURTA VALE, M. H., and PEREIRA, C., “The response of grounding electrodes to lightning currents: the effect of frequency dependent soil resistivity and permittivity,” *IEEE Trans. Electromagnetic Compatibility*, vol. 22, no. 2, pp. 401–406, May 2011.

[27] GUSTAVSEN, B., “Fast passivity enforcement for pole-residue models by perturbation of residue matrix eigenvalues,” *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2278–2285, Oct. 2008.

[28] GUSTAVSEN, B., Matrix Fitting Toolbox [Online]. Available: https://www.sintef.no/projectweb/vectorfitting/, 2020.

[29] ANDERSON, J. G. (1982). Transmission Line Reference Book – 345 kV and Above / Second Edition, chapter 12. Electric Power Research Institute, Palo Alto, California.

[30] DELLALLIBERA, A., ANDRADE, A., BEZERRA, DUARTE, A., GÓIS, J., P., and MARKIEWICZ, R.. “Brazilian production development of class 2 polymeric surge arresters for transmission line application (TLA)” in *Proc. of Conference: Application of Line Surge Arresters in Power Distribution and Transmission Systems – CIGRÉ,* Cavtat, Croatia, 2008.

ÍNDICE REMISSIVO

ENGENHARIA ELÉTRICA:

COMUNICAÇÃO INTEGRADA NO UNIVERSO DA ENERGIA

www.atenaeditora.com.br
contato@atenaeditora.com.br
@atenaeditora
www.facebook.com/atenaeditora.com.br

Atena
Editora
Ano 2021

ENGENHARIA ELÉTRICA:

COMUNICAÇÃO INTEGRADA NO UNIVERSO DA ENERGIA

www.atenaeditora.com.br
contato@atenaeditora.com.br
@atenaeditora
www.facebook.com/atenaeditora.com.br

Atena Editora
Ano 2021