

Weiming Ma · Mingzhe Rong ·  
Fei Yang · Wenfeng Liu ·  
Shuhong Wang · Gengfeng Li *Editors*

# The Proceedings of the 9th Frontier Academic Forum of Electrical Engineering

Volume I

# Lecture Notes in Electrical Engineering

## Volume 742

### Series Editors

Leopoldo Angrisani, Department of Electrical and Information Technologies Engineering, University of Napoli Federico II, Naples, Italy  
Marco Arteaga, Departament de Control y Robótica, Universidad Nacional Autónoma de México, Coyoacán, Mexico  
Bijaya Ketan Panigrahi, Electrical Engineering, Indian Institute of Technology Delhi, New Delhi, Delhi, India  
Samarjit Chakraborty, Fakultät für Elektrotechnik und Informationstechnik, TU München, Munich, Germany  
Jiming Chen, Zhejiang University, Hangzhou, Zhejiang, China  
Shanben Chen, Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, China  
Tan Kay Chen, Department of Electrical and Computer Engineering, National University of Singapore, Singapore, Singapore  
Rüdiger Dillmann, Humanoids and Intelligent Systems Laboratory, Karlsruhe Institute for Technology, Karlsruhe, Germany  
Haibin Duan, Beijing University of Aeronautics and Astronautics, Beijing, China  
Gianluigi Ferrari, Università di Parma, Parma, Italy  
Manuel Ferre, Centre for Automation and Robotics CAR (UPM-CSIC), Universidad Politécnica de Madrid, Madrid, Spain  
Sandra Hirche, Department of Electrical Engineering and Information Science, Technische Universität München, Munich, Germany  
Faryar Jabbari, Department of Mechanical and Aerospace Engineering, University of California, Irvine, CA, USA  
Limin Jia, State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing, China  
Janusz Kacprzyk, Systems Research Institute, Polish Academy of Sciences, Warsaw, Poland  
Alaa Khamis, German University in Egypt El Tagamoa El Khames, New Cairo City, Egypt  
Torsten Kroeger, Stanford University, Stanford, CA, USA  
Qilian Liang, Department of Electrical Engineering, University of Texas at Arlington, Arlington, TX, USA  
Ferran Martín, Departament d'Enginyeria Electrònica, Universitat Autònoma de Barcelona, Bellaterra, Barcelona, Spain  
Tan Cher Ming, College of Engineering, Nanyang Technological University, Singapore, Singapore  
Wolfgang Minker, Institute of Information Technology, University of Ulm, Ulm, Germany  
Pradeep Misra, Department of Electrical Engineering, Wright State University, Dayton, OH, USA  
Sebastian Möller, Quality and Usability Laboratory, TU Berlin, Berlin, Germany  
Subhas Mukhopadhyay, School of Engineering & Advanced Technology, Massey University, Palmerston North, Manawatu-Wanganui, New Zealand  
Cun-Zheng Ning, Electrical Engineering, Arizona State University, Tempe, AZ, USA  
Toyoaki Nishida, Graduate School of Informatics, Kyoto University, Kyoto, Japan  
Federica Pascucci, Dipartimento di Ingegneria, Università degli Studi "Roma Tre", Rome, Italy  
Yong Qin, State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing, China  
Gan Woon Seng, School of Electrical & Electronic Engineering, Nanyang Technological University, Singapore, Singapore  
Joachim Speidel, Institute of Telecommunications, Universität Stuttgart, Stuttgart, Germany  
Germano Veiga, Campus da FEUP, INESC Porto, Porto, Portugal  
Haitao Wu, Academy of Opto-electronics, Chinese Academy of Sciences, Beijing, China  
Junjie James Zhang, Charlotte, NC, USA

The book series *Lecture Notes in Electrical Engineering* (LNEE) publishes the latest developments in Electrical Engineering - quickly, informally and in high quality. While original research reported in proceedings and monographs has traditionally formed the core of LNEE, we also encourage authors to submit books devoted to supporting student education and professional training in the various fields and applications areas of electrical engineering. The series cover classical and emerging topics concerning:

- Communication Engineering, Information Theory and Networks
- Electronics Engineering and Microelectronics
- Signal, Image and Speech Processing
- Wireless and Mobile Communication
- Circuits and Systems
- Energy Systems, Power Electronics and Electrical Machines
- Electro-optical Engineering
- Instrumentation Engineering
- Avionics Engineering
- Control Systems
- Internet-of-Things and Cybersecurity
- Biomedical Devices, MEMS and NEMS

For general information about this book series, comments or suggestions, please contact [leontina.dicecco@springer.com](mailto:leontina.dicecco@springer.com).

To submit a proposal or request further information, please contact the Publishing Editor in your country:

**China**

Jasmine Dou, Editor ([jasmine.dou@springer.com](mailto:jasmine.dou@springer.com))

**India, Japan, Rest of Asia**

Swati Meherishi, Editorial Director ([Swati.Meherishi@springer.com](mailto:Swati.Meherishi@springer.com))

**Southeast Asia, Australia, New Zealand**

Ramesh Nath Premnath, Editor ([ramesh.premnath@springernature.com](mailto:ramesh.premnath@springernature.com))

**USA, Canada:**

Michael Luby, Senior Editor ([michael.luby@springer.com](mailto:michael.luby@springer.com))

**All other Countries:**

Leontina Di Cecco, Senior Editor ([leontina.dicecco@springer.com](mailto:leontina.dicecco@springer.com))

**\*\* This series is indexed by EI Compendex and Scopus databases. \*\***

More information about this series at <http://www.springer.com/series/7818>

Weiming Ma · Mingzhe Rong · Fei Yang ·  
Wenfeng Liu · Shuhong Wang · Gengfeng Li  
Editors

# The Proceedings of the 9th Frontier Academic Forum of Electrical Engineering

Volume I

 Springer

*Editors*

Weiming Ma  
Naval University of Engineering  
Wuhan, Hubei, China

Mingzhe Rong  
Xi'an Jiaotong University  
Xi'an, Shaanxi, China

Fei Yang  
Xi'an Jiaotong University  
Xi'an, Shaanxi, China

Wenfeng Liu  
Xi'an Jiaotong University  
Xi'an, Shaanxi, China

Shuhong Wang  
Xi'an Jiaotong University  
Xi'an, Shaanxi, China

Gengfeng Li  
Xi'an Jiaotong University  
Xi'an, Shaanxi, China

ISSN 1876-1100

ISSN 1876-1119 (electronic)

Lecture Notes in Electrical Engineering

ISBN 978-981-33-6605-3

ISBN 978-981-33-6606-0 (eBook)

<https://doi.org/10.1007/978-981-33-6606-0>

© Beijing Oriental Sun Cult. Comm. CO Ltd 2021

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.  
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

# Committees

## Honorary Chairman

Chen Weijiang (Academician of the Chinese Academy of Sciences)

## Chairman

Prof. Yang Qingxin (Chairman of China Electrotechnical Society and President of Tianjin University of Technology)

Prof. Rong Mingzhe (Vice President of China Electrotechnical Society and Vice President of Xi'an Jiaotong University)

## Academic Committees

### Chairman

Ma Weiming (Academician of the Chinese Academy of Engineering)

### Vice-Chairman

Cheng Yonghong (Xi'an Jiaotong University)

Prof. Yuan Fuxing (Deputy General Manager of Xi'an High Voltage Apparatus Research Institute)

### Secretary-General

Prof. Guo Lijun (Director of Editorial Department of Chinese Journal of Electrotechnical Technology)

Prof. Yang Fei (Xi'an Jiaotong University)

### Deputy Secretary-General

Prof. Liu Wenfeng (Xi'an Jiaotong University)

Prof. Liu Dingxin (Xi'an Jiaotong University)

Prof. Wang Laili (Xi'an Jiaotong University)  
Prof. Han Xiaogang (Xi'an Jiaotong University)  
Prof. Li Gengfeng (Xi'an Jiaotong University)  
Prof. Meng Guodong (Xi'an Jiaotong University)  
Prof. Michael Tai Ching Fang, University of Liverpool, UK  
Prof. Anthony B. Murphy, CSIRO Manufacturing, Australia  
Prof. Yasunori Tanaka, Kanazawa University, Japan  
Prof. Yann Cressault, Université de Toulouse, France  
Prof. Jiudun Yan, University of Liverpool, UK

## **Organizing Committees**

### **Chairman**

Prof. Wang Jianhua (Director, State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University)

### **Vice-Chairman**

Prof. Li Shengtao (Executive Deputy Dean of Xi'an Jiaotong University)  
Prof. Wang Jiansheng (General Manager of Xi'an High Voltage Apparatus Research Institute)

### **Secretary-General**

Wang Wenguang (Deputy Director, Editorial Department, China Electrotechnical Society)  
Wang Yusheng (Deputy Director, Editorial Department, China Electrotechnical Society)  
Jia Yuquan, Shanghai PIBO Information Technology Center, China  
Liang Weihong (Xi'an High Voltage Apparatus Research Institute)  
Prof. Wang Shihang (Xi'an Jiaotong University)  
Prof. Anthony B. Murphy, CSIRO Manufacturing, Australia  
Prof. Yann Cressault, Université de Toulouse, France  
Prof. Jiudun Yan, University of Liverpool, UK

# Contents

<b>Design of Dynamic Wireless Charging System for Inspection Robot</b> . . . .	1
Xiaokang Wu, Cheng Jiang, Bowei Dong, Hao He, and Songcen Wang	
<b>Causes Analysis of Burst Fault for 500 kV Porcelain Bushing Based on Explosion Theory</b> . . . . .	11
Jianli Zhao, Yonggang Yue, Zhuo Liu, Shuhua Yao, and Lanjun Yang	
<b>Coordinated Optimization of Multi-Machine PSS Based on Improved Gravitational Search Algorithm</b> . . . . .	25
Wei Liu, Yupeng Guo, Fanglin Lv, and Wendi Yan	
<b>Design of Position Sensorless Controller for BLDC Cooling Fan</b> . . . . .	35
Huang Qi, Xi Wei, Wang Sheng, and Wu Quan	
<b>Observation of Positive Streamer Branches in a Long Air Gap</b> . . . . .	47
Chuanqi Wu, Jun Chen, Hengxin He, and Junjia He	
<b>Experimental Study on the Electrical Insulation Characteristics of R124</b> . . . . .	57
Jianhui Chen, Guomin Zhang, Qingquan Qiu, Xiaogang Chen, Yuping Teng, and Liwei Jing	
<b>The Effect of Axial Magnetic Field on the Lifetime of Micro Cathode Arc Thruster (<math>\mu</math>-CAT)</b> . . . . .	69
Guan Wang, Zhiyuan Cao, Boyang Chen, Zhenxing Wang, and Liqiong Sun	
<b>Transmission Lines Monitoring Based on Convolution Neural Network and Edge Computation</b> . . . . .	79
Yue Guo, Huan Yuan, Jinguo Zhu, Lujin Wang, Aijun Yang, and Xiaohua Wang	
<b>Design of a Power Transmission Line On-line Monitoring System Based on A/B Interface Grid Protocols</b> . . . . .	89
Lujin Wang, Huan Yuan, Xiaohua Wang, Yue Guo, and Aijun Yang	

<b>A Novel PLL for Auxiliary Supply System in Railway Vehicles</b> .....	99
Chengwei Kang, Yang Lin, Weijie Li, and Ping Wang	
<b>Characteristics Research on Compact and Light-Weight IPT System Based on LCCN Compensation</b> .....	109
Di Zhang, Guorong Zhu, Jianghua Lu, Kai Du, and Jing V. Wang	
<b>Research on High Precision AC Voltage Phase and Amplitude Detection Algorithms Based on SPLL and CORDIC</b> .....	123
Chengwei Kang, Ping Wang, and Weijie Li	
<b>The Arc Ignition Mode Between Wan-Type Transverse Magnetic Field Contacts</b> .....	133
Jiashuo Cui, Shixin Xiu, Rui Li, Tao Liu, and Mengru Li	
<b>Influence of Slot Number on the Vacuum Arc Characteristics Between Spiral-Type Transverse Magnetic Field Contacts</b> .....	145
Tao Liu, Shixin Xiu, Rui Li, Jiashuo Cui, Dingyu Feng, and Gang Liu	
<b>Study on the Decomposition Pathways and Products of <math>C_4F_7N/N_2</math></b> .....	157
Li Haoyang, Fu Yuwei, Zheng Borui, Wang Xinxin, and Duan Jiandong	
<b>Line-Frequency Instability of Single-Stage PFC Flyback Converter: Theoretical Analysis and Experimental Validation</b> .....	165
Taizhi Zhang, Yimin Zhou, and Ziping Bai	
<b>Finite Element Analysis of Dynamic Contact Stress of Spur Gear Based on ANSYS</b> .....	177
Canjiang Yao, Fuyong Li, Longyong Sun, Gang Xu, Panke Yuan, Yingying Liu, Guang Yang, Fuya Wang, Bingcan Gao, and Yingfeng Jia	
<b>Research on Key Influence Factors of Independent Double Three-Phase Common-Bus Five-Level NPC/H Bridge Inverter DC-Link Capacitor Voltage Fluctuation</b> .....	189
Wei Wang, Guangsen Wang, Bin Zhou, and Zhenyu Zhang	
<b>Experimental Study on the Relationship Between Ablation of Circuit Breaker Electrical Life and Dynamic Resistance</b> .....	199
Rui Cao, Hong-hong Lv, Xing Wu, Hao Wang, Pei Zhao, Zhao-zhao Xin, Hao-jun Liu, and Wen Gao	
<b>Influence of Micro-structure Disorder in the Numerical Modeling of Metal Oxide Varistor on Current Distribution</b> .....	211
Qibin Zhou, Hongxiang Yang, and Xin Huang	
<b>A Narrow Pulses Less NL-PWM Method for Cascaded Converter with Improved Harmonic Characteristics Under Reduced Switching Frequency</b> .....	221
Jie Mu, Yonghai Xu, Xueyin Zhang, and Yibo Ding	

**Radiation Magnetic Field Research of Primary/Secondary Fusion Switch Cabinet Based on Frequency Scaling Approach** ..... 235  
 Wenchao Lu, Jiandong Duan, Zainan Li, Xiaotong Du, and Linyun Guo

**A Five-Level Unidirectional Rectifier for Medium Input Voltage High-Power Chargers** ..... 243  
 Shuai Wu and LiYong Niu

**A Fuzzy Logical Threshold Strategy for Optimal Fuel Efficiency of Diesel Engine Based Series Heterogeneous Multi-Energy Drive System** ..... 257  
 Xiaoyu Ren, Gengyi Lin, Xinyue Zhang, and Lijun Diao

**Optimal Scheduling of Integrated Microgrids with High Resolution Islanding** ..... 267  
 Yu Chen

**Analytical Model for Inter-harmonics Current Caused by MPPT of Grid-Connected PV System in LV Network** ..... 275  
 Wanwan Xu, Bin Wang, and Jiang Liu

**An Inductance Extraction Method for SiC Converter Loop of EMU Emergency Self-Running Supply** ..... 287  
 Shuquan Song, Yutong Zhu, Bo Liu, Tengfei Qiu, Yiheng Chen, and Lijun Diao

**The Innovative Application of Power Data Platform Construction Based on Blockchain Technology** ..... 299  
 Xun Hua and Han Xunjie

**Input-Series-Output-Parallel LLC Resonant Converter with Input Power Factor Correction for AGV Chargers** ..... 309  
 AiFeng Sun and LiYong Niu

**Overvoltage Protection Performance of Series Compensation in Transmission System** ..... 319  
 Xiaotong Song, Qiannan Lyu, Yuxin Zhao, and Yi Sun

**Magnetic Field Mapping in the Magnetic Resonance Imaging System Using Genetic Algorithms** ..... 331  
 Junjie Huang, Li Huang, and Shenli Wang

**Auto-Transformer and Magnetic Control Soft Start Method for Super Large Capacity and High Voltage Motor** ..... 339  
 Xinyi Yang and Chuansheng Wang

**Simulation of Magnetic Field Controlled Plasma One-Dimension Jet Array** ..... 351  
 Changquan Wang and Haiyun Luo

<b>Numerical Simulation Calculation Analysis of Very Fast Transient Overvoltage Arcing Characteristics in GIS Under Dynamic Arc Model</b> .....	359
Ruming Feng, Chuanqiang Che, Jianli Zhao, Zhilin Liu, Lei Zhao, and Qiong Wang	
<b>Adaptive Control of BESS and HVAC for Primary Frequency Regulation</b> .....	369
Shuchen Luo, Long Zhou, Hao Yu, Gang Yao, and Canbing Li	
<b>Adaptive Over-Frequency Response Control for Wind Farm to Participate the System Frequency Regulation</b> .....	381
Kang Wang, Tianhu Wan, Hua Li, Kun Huang, and Peng Kou	
<b>Full Speed Position Estimation Based on Disturbance Observer and HF Signal Injection for IPMSM Sensorless Control</b> .....	391
Xiaoquan Lu, Hanmiao Cheng, Xiaodong Cao, Shihai Yang, and Fei Peng	
<b>Research on Fast-Cooling Extinguishing Agent for Lithium-Ion Battery Fire</b> .....	407
Jie Tian, Lin Wu, Yan Li, Yuming Zhao, and Yuan-Cheng Cao	
<b>A Novel Integrated On-Board Charger Based on Dual-Motor Drive System for Electric Vehicles</b> .....	417
Guangqian Shan and Qiang Song	
<b>Complex-Vector Modeling of DFIG-Based Wind Turbine Riding Though Weak AC Grid Voltage Dips</b> .....	429
Yufeng Zhang, Hailiang Xu, and Shinan Wang	
<b>Analysis for Research Achievements and Progress Trends of Underwater Electric-Field Coupled Wireless Power Transfer</b> .....	441
Qiao Xiong, Ying Shao, Jun Sun, Pan Sun, Jin Cai, and Xin-Yi Song	
<b>Coordinated Control of the Grid-Side and Machine-Side Converters of D-PMSG Under Unbalanced and Distorted Grid Voltage Conditions</b> .....	457
Shinan Wang, Hailiang Xu, and Yufeng Zhang	
<b>Advanced Configuration and Control Strategy of Variable Frequency Transformer to Minimize Torque and Power Fluctuations Under Asymmetrical Grid Faults</b> .....	469
Jiahao Lu, Jincheng Yang, Qining Bai, Yongqiang Feng, and Sizhe Chen	
<b>Sliding Mode Control of Permanent Magnet Synchronous Motor with Improved Variable Exponential Reaching Law</b> .....	479
Ningqun Zhou, Qiao Zhang, and Qiyi Zeng	

**The Research and Development of a Novel Substation-Area Protection Device** ..... 489  
 Xuanwei Qi, Song Wang, Yutao Qiu, Heming Wang, Xiaojiang Zheng, and Yincheng Wang

**Neural Network Based Maximum Power Point Tracking Scheme for PV System Under Partially Shaded Conditions** ..... 499  
 Lv Chenghao, Li Henghao, Sui Jiacheng, Hou Zongrun, and Chi Xiaohong

**Study on VFTO and Its Electromagnetic Disturbance Characteristics Caused by GIS Isolation Switch Operation** ..... 511  
 Cheng Lin, Huang Xingming, Xu Weifeng, Yuan Jiaxin, Liu Jian, and Wu Jingfeng

**Control Strategy and Economic Analysis of Wind Power with Energy Storage Participating in Grid Frequency Regulation** ..... 523  
 Gong Yu, Liu Hui, Song Peng, and Shao Yinchu

**A Simplified SVPWM Method Applied to Subway Traction Inverter** ... 537  
 Chengwei Kang, Peicheng Cong, and Zichen Gao

**Analysis and Optimization of Wireless Power Transmission Magnetic Coupling Structures Based on DD Coil** ..... 547  
 Binbin Han, Xikui Ma, Jinghui Shao, Wei Liu, Wenjing Zhang, Zhiyu Li, and Jiawei Wang

**Improved Equivalent Model of LLC Converter Considering Distribution Parameters of Transformer** ..... 557  
 Yuming Zhao, Xiaomin Xin, Guowei Liu, and Jing Wang

**Research on Optimal Configuration of High Speed Railway Energy Storage System Considering Full Life Cycle** ..... 569  
 Xianfeng Zheng, Jiaxin Yuan, and Kai Qu

**First-Principles Modeling and Calculations of HfO<sub>2</sub>/Si Interface in Nano Devices** ..... 581  
 Jiachi Yao, Guanghao Qu, Guowei Zhang, Daomin Min, and Jie Liu

**Study on Elasto-Plastic Deformation Characteristics of Micro-Bumps on Electrical Contact Surface** ..... 595  
 Qi Liu, Xiaonan Zhu, Junxingxu Chen, Hang Lei, Chunping Niu, Haoran Wang, Lei Wang, and Fei Yang

**Noncontact ECG Measuring System Based on Capacitive PCB Electrodes** ..... 607  
 Yifeng Wang, Zhengyi Xu, Shuhan Liu, Zhifeng Dai, and Jiangtao Li

**Investigation on Mathematical Model of Electric Contact Based on Fractal Geometry** ..... 617  
 Hang Lei, Xiaonan Zhu, Haoran Wang, Junxingxu Chen, Qi Liu, Chunping Niu, Lei Wang, and Fei Yang

**An Internal AC Self-Heating Method Based on On-Board Charger for Lithium-Ion Batteries Preheating** ..... 629  
 Biaoming Hong and Furong Liu

**Adaptive Control Strategy of Intelligent Electromagnetic Contactor Based on Data-Driven** ..... 637  
 Yang Wang and Zhihong Xu

**Impedance Modeling and Stabilization Control of Grid-Connected Inverter under Weak Grid** ..... 647  
 Lei Huang

**Design and Modeling of Diesel-Electric Hybrid Shunting Locomotive** ..... 655  
 Jian Wu, Qiao Ji, Chi Zhang, Zhenlin Zhu, Bin Zhao, and Ze Yin

**Correlation Analysis of Influencing Factors of Switching Impulse Discharge Voltage in Rod-Plane Air Gap** ..... 667  
 Xiuyuan Yao, Bingxue Yang, Zhanhui Lu, Ge Xing, and Ding Yujian

**A Big Data Technology-Based Approach to Power Neural Network Analysis** ..... 677  
 Qionglan Na, Jing Lou, Yixi Yang, Dan Su, Jia Wu, and Jing Zeng

**Energy Transfer Characteristics of Contactless Power Transfer System in Different Media** ..... 689  
 Yongshan Jiang, Weiyao Mei, Lijun Diao, Chunhui Miao, Zhijie Zhang, and Yuying Zhou

**An Auxiliary Circuit for Synchronous Buck Converter to Achieve All Switches ZVS/ZCS Switching in Wide Load Range** ..... 699  
 Jinwei Zhong, Bingyang Luo, Song Xiong, and Guorong Zhu

**A ZVS Soft-Charging Switched-Capacitor Converter** ..... 709  
 Yizhou Huang, Bingyang Luo, Song Xiong, and Guorong Zhu

**Protection of Lightning Indirect Effect for Power Supply System for Flight Test Equipment of C919 Airplane** ..... 719  
 Jing Li, Hongjuan Ge, Yinxiao Hu, and Lin Liu

**Research on Speed-Loop Control Strategy of Dynamic Load Simulators for Electric Vehicle Powertrain** ..... 731  
 Yanlin Li and Huafeng Xia

**Magnet Shape Optimization for Reduction of Cogging Torque in MSPMSG by Using the Taguchi Method** ..... 741  
 Zhou Ran, Meng Keqilao, Jia Dajiang, Hai Rihan, and Wang Teng

**Bidirectional ICPT Harmonic Elimination System Based on Harmonic Extraction and Inverse Injection Method** ..... 751  
 Xvdong Li and Ruoqiong Li

**Robust Initial Rotor Position Estimation for SPMSM Based on High Frequency Pulsating Voltage Injection** ..... 763  
 Yongle Mao and Jun Ma

**Review of Regenerative Braking Energy Storage and Utilization Technology in Urban Rail Transit** ..... 775  
 Lesheng Xing and Xin Li

**Modelling Research on the Mechanism of Non-contact ECG Measurement Based on Capacitive Coupling** ..... 785  
 Zhengyi Xu, Yifeng Wang, Xinlei Zheng, Raza Syed Ali, and Jiangtao Li

**Nanotip Shape Evolution Under High Electric Fields Based on Molecular Dynamics** ..... 795  
 Xinyu Gao, Bing Xiao, Nan Li, Ziang Jing, Chengye Dong, Guodong Meng, and Yonghong Cheng

**Three-Dimensional Electric Field Simulation Analysis of Typical Defects in Medium Voltage XLPE Cable Joint** ..... 805  
 Liqiu Huang, Hong Xu, Xuming Wang, Jiahao Qian, and Jianyong Lou

**A New Principle of Active Arc Suppression for Distribution Network Based on Constant Fault Phase Current** ..... 817  
 Jian Xue, Hao Liu, Guobing Song, Yuanyang Wang, and Zhirong Lei

**Control Strategy for Smooth Switching and Off-Grid Stable Operation of Multi-energy Complementary Microgrid** ..... 827  
 Yinghua Lu, Xinran Li, Xiaolong Liu, Zhipu Liu, and Zhen Luo

**Research on Multi-target Tracking and Positioning Method in Substation Scene** ..... 839  
 Yan Dai, Rui Han, Zhongguang Yang, Xinyue Zhang, Linfeng Chen, and Shuang Liu

**Research on the Application of Blockchain Technology in the Construction of Power Internet of Things** ..... 853  
 Qionglan Na, Dan Su, Yixi Yang, Jing Lou, Jia Wu, and Jing Zeng

**Investigation on the Arc Behaviors in the Oil Aiming for the Applications of On-load Tap Changer in the Transformer** ..... 865  
 Luqi Liang, Wei Huang, Hao Sun, Yanwei Nan, and Fei Yang

# Design of Dynamic Wireless Charging System for Inspection Robot



Xiaokang Wu, Cheng Jiang, Bowei Dong, Hao He, and Songcen Wang

**Abstract** In this paper, based on the research background of dynamic wireless charging of inspection robot in substation, the magnetic coupling structure and compensation network suitable for wireless charging system of robot are selected, and the transient and steady-state process in the whole process of robot operation is analyzed. According to the analysis results, the corresponding guide rail switching scheme is developed. Combined with the characteristics of the inspection robot that needs precise control, the acceleration sensor and photoelectric sensor collect multiple motion information, accurately locate the robot, and use the FPGA module to process the data in parallel at high speed to control the guide rail at the same time. Finally, the system is verified to be fast by building an experimental platform And the transmission coil on the power supply guide rail is accurately controlled to switch, which ensures the maximum operation power and efficiency of the system.

**Keywords** Wireless charging · FPGA · Rail switching

## 1 Introduction

Wireless power transmission technology as a new technology, compared with the traditional electric vehicle wired charging method, has the advantages of no direct contact, convenient charging, small environmental pollution, strong environmental adaptability and so on, so it has been widely valued. However, due to the problems of static wireless charging, such as frequent charging, short range, large battery consumption and high cost, many experts and scholars have conducted extensive research on dynamic wireless charging technology [1–5]. Dynamic wireless charging can be divided into single coil long guide rail type [6, 7] and multi coil segmented

---

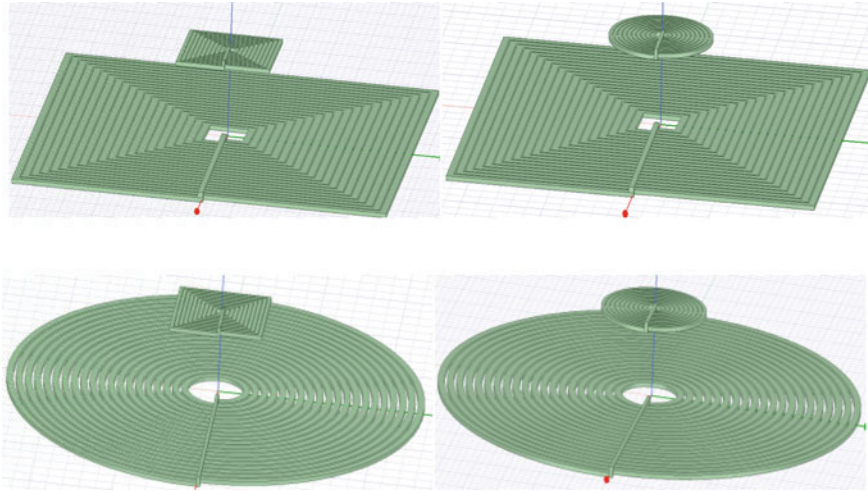
X. Wu · C. Jiang · B. Dong (✉) · H. He · S. Wang  
China Electric Power Research Institute, No. 15 Xiaoying East Road, Qinghe,  
Beijing 100192, China  
e-mail: [wu6202168@163.com](mailto:wu6202168@163.com)

B. Dong  
Beijing Jiaotong University, Haidian District, 3 Shangyuan Village, Beijing 100044, China

guide rail type [4, 8, 9] according to different layout of transmitting coil. There are many problems of electromagnetic leakage and low transmission efficiency in the layout of single coil long guide rail, while the segmented guide rail reduces unnecessary electromagnetic leakage and energy loss through switching control. Therefore, at present, most of the dynamic wireless charging systems adopt the layout mode of multi transmit coil section guide rail. As one of the important parts of the dynamic wireless charging system, the design of the rail switching system will affect the power and efficiency of the whole system. In this regard, in reference [6], the magnetic field of the transmitting coil is measured in real time through the three-axis magnetic field strength sensor, so as to achieve the purpose of positioning the receiving coil and realize the rail switching control. In Ref. [9], photoelectric sensors are installed on both sides of the transmitting coil to locate the position of the electric vehicle, so as to realize the rail switching. In Ref. [4], the primary coil relay power supply with decentralized control logic is realized by using the secondary active excitation detection. Most of the above literature is about the switching control scheme of electric vehicles. Due to the small receiving coil area, high control accuracy and speed requirements, the robot only operates in a certain area, which is different from the electric vehicle. Therefore, this paper designs a dynamic wireless charging system for wireless charging of inspection robot in substation. Because FPGA chip has the advantages of high-speed parallel processing information [10], the system uses FPGA chip for data processing and system control. The acceleration information of the robot is collected by the acceleration sensor, and the information is transmitted to the control chip through wireless communication. At the same time, the position information of the robot is collected by the photoelectric sensor. After the information is comprehensively processed by the FPGA chip, the control signal is output according to the preset power and efficiency requirements of the wireless charging system, and the control relay is turned on or off, and then the transmitting coil is turned on Switch between on and off.

## 2 Magnetic Coupling Structure and Compensation Network Design

Magnetic coupling structure is the general designation of transmitting coil and receiving coil in wireless charging system. It can transform high-frequency alternating current into high-frequency magnetic field for energy transmission. Therefore, the selection of magnetic coupling structure has an important impact on the power and efficiency of the system. At present, there are four types of magnetic coupling structure: rectangle circle, rectangle rectangle, circle rectangle and circle circle. For the dynamic wireless charging system designed in this paper, the change of system power and efficiency with the offset distance between the transmitting coil and the receiving coil is the primary index to measure the performance of a dynamic wireless charging system. Therefore, in ANSYS Maxwell, the above four types of magnetic

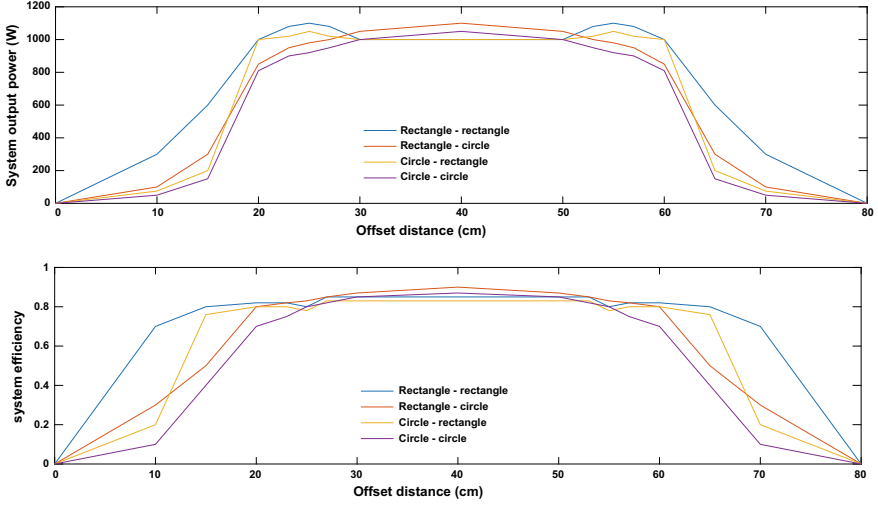


**Fig. 1** Magnetic coupling structure simulation diagram

coupling structure are analyzed The magnetic coupling structure is simulated, as shown in Fig. 1.

Under the same control input voltage (200 V), circuit topology (LCC-S), load resistance ( $5\Omega$ ) and other conditions, the power and efficiency of the system change with the offset distance between the transmitting coil and the receiving coil when the system adopts four types of structures: rectangle circle, rectangle rectangle, circle rectangle and circle circle. The results are shown in Fig. 2. Among them, the rectangular transmitting coil is  $80 * 80$  cm, the rectangular receiving coil is  $20 * 20$  cm, the circular transmitting coil is 80 cm in diameter, the circular receiving coil is  $20 * 20$  cm, and the distance between the transmitting coil and the receiving coil is 8 cm.

Through the analysis of the above simulation results, it can be found that the slope of the power and efficiency curve of the system is large when the transmitting coil is of rectangular structure, and will remain at a certain value after reaching the extreme value. When the transmitting coil is of circular structure, the slope of the power and efficiency curve of the system is relatively small, and it keeps growing until the center of the transmitting coil is positive to the center of the receiving coil. In addition, the power and efficiency of the receiving coil with rectangular structure is slightly higher than that of the receiving coil with circular structure. For static wireless charging, it is required to have high power and efficiency at a certain fixed position, so it is better to use circular transmitting coil in static wireless charging, but for dynamic wireless charging, it is required that the power and efficiency increase to the maximum value with the offset distance quickly, and can maintain stable power and efficiency at a certain distance, so the transmitting coil is rectangular. More suitable for dynamic wireless charging. Considering that the inspection robot is smaller than electric vehicles and trams, which may be affected by external forces in the operation process and lead to the situation of separation from the guide rail, it



**Fig. 2** The variation trend of power and efficiency of the system with the offset distance between transmitting coil and receiving coil

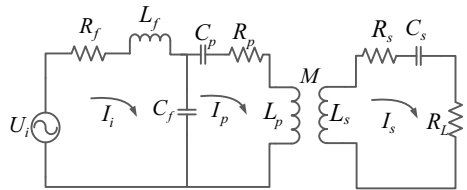
is necessary to select a compensation network that can keep the system current in a safe range when the receiving coil leaves.

The LCC-S circuit structure selected in this paper is shown in Fig. 3. According to Kirchhoff's current law, the AC input current, resonance current on the transmitting coil and resonance current on the receiving coil are calculated as:

$$\begin{cases} I_i = \frac{R_p(R_s + R_L) + \omega^2 M^2}{X_{C_f}^2(R_s + R_L)} V_i \approx \frac{\omega^2 M^2}{X_{C_f}^2 R_L} V_i \\ I_p = \frac{1}{jX_{C_f}} V_i \\ I_s = \frac{\omega M}{X_{C_f}(R_s + R_L)} V_i \approx \frac{\omega M}{X_{C_f} R_L} V_i \end{cases} \quad (1)$$

After the whole output receiving side leaves, the branch is disconnected, and the current changes to:

**Fig. 3** LCC-S circuit structure



$$\begin{cases} I_i = \frac{R_p}{X_{Cf}^2} V_i \\ I_p = \frac{1}{jX_{Cf}} V_i \end{cases} \quad (2)$$

It can be found that the system is still in a safe state. Therefore, LCC-S compensation network meets the needs of wireless charging system design of inspection robot.

### 3 Electromagnetic Transient Analysis of System Switching Process

Wireless charging guide rail switching is divided into soft switching and hard switching. Soft switching refers to reducing the power supply in advance when the inspection robot is about to leave the current guide rail, turning off the guide rail after the power supply voltage drops to 0, opening the next guide rail before the inspection robot enters the next guide rail, and then boosting the power supply to the rated voltage output value. Hard switching refers to patrol inspection. When the power supply voltage is not 0, the robot directly turns off the current guide rail or opens the next guide rail. The soft switching mode is to switch at the power supply voltage of 0, so there is no impulse voltage in the system during the switching process, which has high security. However, because it needs time for the power supply to be boosted or depressurized, the power and efficiency of wireless charging in the space passing through during this time will be reduced, so there will be some energy waste in the soft switching mode. In the process of hard switching, the components in the system need to bear impulse voltage, which has certain security risks, and puts forward higher requirements for the withstand voltage of system components. However, when the power and efficiency of the system have not been reduced, the hard switching mode can reduce the energy waste in the soft switching mode.

In order to calculate the maximum impulse voltage of circuit components in hard switching mode, the electromagnetic transient model is established by using the state variable method for the circuit structure in Fig. 1. Define AC input  $I_i$  current as state variable  $x_1$ , resonant current  $I_p$  on the transmitting coil as state variable  $x_2$ , Resonance current  $I_s$  on receiving coil as state variable  $x_3$ , Capacitor voltage  $C_f$  is state variable as state variable  $x_4$ , Capacitor voltage  $C_p$  is state variable as state variable  $x_5$ , Capacitor voltage  $C_s$  is state variable as state variable  $x_6$ . From KCL and KVL:

$$\begin{cases} u_i = R_f x_1 + L_f \dot{x}_1 + x_4 \\ x_5 + R_p x_2 + L_p \dot{x}_2 = M \dot{x}_3 + x_4 \\ L_s \dot{x}_3 + x_6 + R_L x_3 + R_s x_3 = M \dot{x}_3 \\ x_1 = C_f \dot{x}_4 + x_2 \\ x_2 = C_p \dot{x}_5 \\ x_3 = C_s \dot{x}_6 \end{cases} \quad (3)$$

Then the state equation matrix of the system is:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{bmatrix} = \begin{bmatrix} -\frac{R_f}{L_f} & 0 & 0 & -\frac{1}{L_f} & 0 & 0 \\ 0 & -\frac{R_p}{L_p} & -\frac{MR_s+MR_L}{L_p(L_s-M)} & \frac{1}{L_p} & -\frac{1}{L_p} & -\frac{M}{L_p(L_s-M)} \\ 0 & 0 & -\frac{R_s+R_L}{L_s-M} & 0 & 0 & -\frac{1}{L_s-M} \\ \frac{1}{C_f} & -\frac{1}{C_f} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C_p} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{C_s} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} + \begin{bmatrix} \frac{u_i}{L_f} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (4)$$

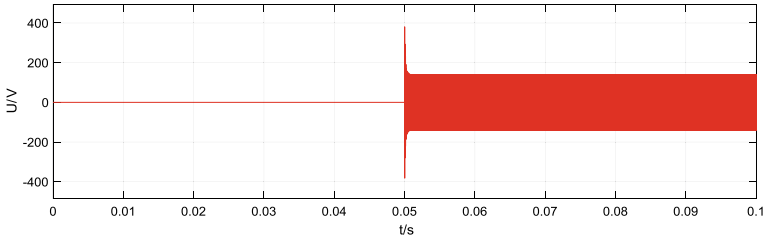
From the time domain method, the state transition matrix can be obtained as Eq. (5), where the matrix A represents the coefficient matrix before the state variable in Eq. (4).

$$\phi(t) = e^{At} = 1 + At + \frac{t^2}{2!}A^2 + \dots + \frac{t^k}{k!}A^k + \dots \quad (5)$$

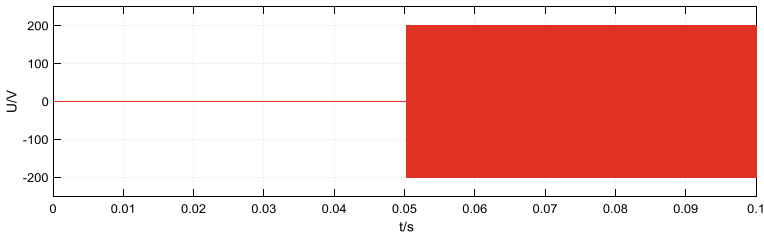
The state transition matrix and initial value of system parameters (relay action time is set to 20 ms) are input into Matlab for simulation, the AC input voltage is set to 100 V. The results is:

$$A = 10^7 * \begin{bmatrix} -0.0031 & 0 & 0 & -0.0016 & 0 & 0 \\ 0 & -0.0014 & -0.0014 & 0.0003 & -0.0003 & -0.0001 \\ 0 & 0 & -2.857 * 10^{-14} & 0 & 0 & -0.0024 \\ 1.8169 & -1.8169 & 0 & 0 & 0 & 0 \\ 0 & 9.9010 & 0 & 0 & 0 & 0 \\ 0 & 0 & 4.3346 & 0 & 0 & 0 \end{bmatrix} \quad (6)$$

It can be seen from Eq. (5) that the absolute value of the resonant current on the transmitting coil and the resonant current on the receiving coil is positively related to the variable mutual inductance m, so the maximum value of mutual inductance m shall prevail when calculating the maximum voltage that the element needs to bear. According to the simulation results, when the transmitting coil and the receiving coil center are aligned, the power supply is directly turned off by hard switching mode.



**Fig. 4** Voltage and current waveforms of resonant inductors during switching



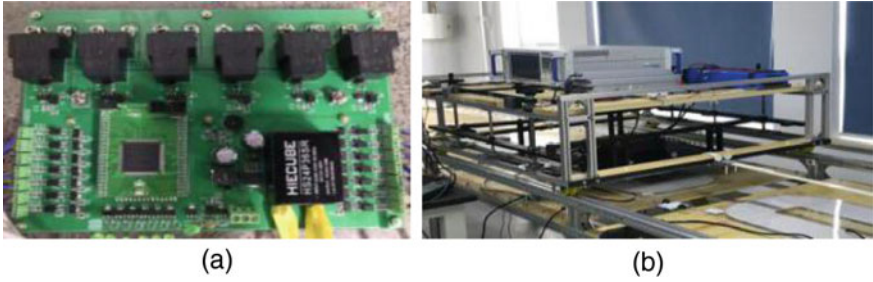
**Fig. 5** Voltage and current waveforms of resonant inductors in the improved switching process

In the dynamic components used in the circuit, the series compensation inductor needs to be able to withstand a maximum impulse voltage of about 400 V. In order to further verify the simulation results, the circuit model is built in Simulink and the hard switch off experiment is carried out. The voltage waveform obtained is shown in Fig. 4. It can be seen from Fig. 4 that 400 V impulse voltage will be borne during direct hard switching, which will obviously cause damage to circuit components.

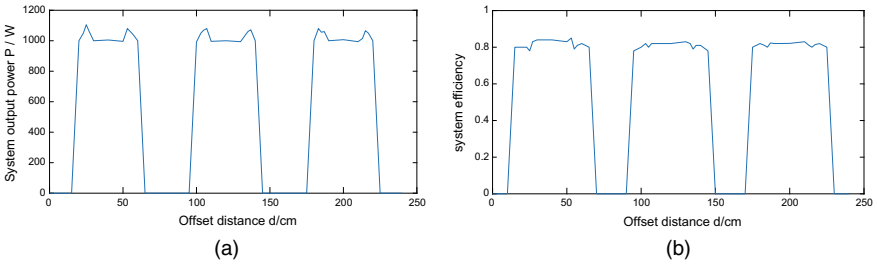
In order to solve this problem, we can choose to add two-stage pre switch in front of the main switch of the original circuit, reduce the voltage of the circuit through two-stage pre switch, and then reduce the impact voltage when the main switch acts. Carry out the hard switch off experiment on the improved circuit model, and the voltage waveform is as shown in Fig. 5. It can be seen from the results in Fig. 5 that the impulse voltage is reduced to about 200 V, which will not cause damage to circuit components.

## 4 Experiment

In order to verify the above control logic and method, a PCB board with FPGA chip as the core is made as shown in Fig. 6a, and a dynamic wireless charging platform for the simulation robot is built as shown in Fig. 6b. The experimental results show that the whole system can be effectively switched, and the devices in the circuit are not burned. The maximum charging efficiency of the system is 88%, and the maximum output power is 1050 W.



**Fig. 6** Experimental site and PCB



**Fig. 7** The transmission power and efficiency of the system

The system output power is shown in Fig. 7a, and the system transmission efficiency is shown in Fig. 7b.

## 5 Conclusion

This paper mainly studies and designs the dynamic wireless charging of inspection robot from the aspects of magnetic coupling structure, compensation network and switching mode. From the above analysis, it can be seen that for the small dynamic wireless charging system represented by inspection robot, rectangular magnetic coupling structure, LCC-S compensation network and hard switching scheme with front switch can ensure the maximum degree of protection. Verify the transmission power and efficiency of the system.

**Acknowledgements** This work was supported by the Science and Technology Project of State Grid Corporation of China “Research on wireless charging technology of underwater cable inspection robot based on new magnetic device”.

## References

1. Jili, Lifang Wang, Chenglin Liao, and Shufan Li. 2018. Research and design of radio energy transmission system based on LCL resonance compensation network with automatic side switching charging mode. *Journal of Electrical Technology* 33 (S1): 34–40.
2. Zhang, Xian, Jie Wang, Qingxin Yang, Bin Wei, and Songcen Wang. 2019. Research on electric energy coupling mechanism and switching control of electric vehicle dynamic wireless charging system. *Journal of Electrical Technology* 34 (15): 3093–3101.
3. Wang, Songcen, and Xiu Han. 2019. Study on the design method of bilateral LCC compensation network parameters of magnetic coupling resonance wireless charging system. *Electrical Technology* 20 (06): 12–16.
4. Zhao, Jinbo, Tao Cai, Shanxu Duan, Hao Feng, and Xiaoming Zhang. 2016. Relay method for segmented dynamic wireless charging. *Power System Automation* 40 (16): 64–70.
5. Zhang, Bo., Xujian Shu, and Runhong Huang. 2017. Development of inductive and harmonic radio energy transmission technology. *Journal of Electrical Technology* 32 (18): 3–17.
6. Shin, J., S. Shin, Y. Kim, et al. 2014. Design and implementation of shaped magnetic-resonance-based wireless power transfer system for roadway-powered moving electric vehicles. *IEEE Transactions on Industrial Electronics* 61 (3): 1179–1192.
7. Ko, Y.D., and Y.J. Jang. 2013. The optimal system design of then online electric vehicle utilizing wireless power transmission technology. *IEEE Transactions on Intelligent Transportation System* 14 (3): 1255–1265.
8. Zhu, Wenji, Yue Sun, and Lik Gao. 2016. Multi rail wireless charging method for electric vehicles. *Power System Automation* 40 (18): 97–101.
9. Sun, Yue, Yong Tian, Su. Yugang, and Zhihui Wang. 2013. Efficient distribution scheme of electric vehicle online power supply system. *Journal of Southwest Jiao Tong University* 48 (02): 236–242.
10. Wang, Yi., Ziqiao Deng, Guoliang Ma, Huian Wen, Jun Ye, Xingzhe Hou, Hongliang Sun, and Ke. Zheng. 2018. Design and implementation of multi node power line channel simulator based on FPGA. *Power System Protection and Control* 46 (17): 145–151.

# Causes Analysis of Burst Fault for 500 kV Porcelain Bushing Based on Explosion Theory



Jianli Zhao, Yonggang Yue, Zhuo Liu, Shuhua Yao, and Lanjun Yang

**Abstract** In this paper, a burst fault occurred in the normal operation of a porcelain bushing for 500 kV tank circuit breaker is considered. Based on the explosion theory, the energy range and the mechanism of the chemical and physical explosion of the porcelain bushing were calculated through the analysis of the projective kinetic energy of the porcelain block, the 3D dynamic simulation of the explosion process and the physical and chemical analysis of the ceramic fragments. On this basis, the characteristics and reasons of the explosion of porcelain bushing were systematically analyzed. The results show that the chemical explosion energy of porcelain bushing is estimated as 55–75 g TNT according to the fragmentation distance of porcelain fragments, which is much larger than the energy generated by physical explosion. Thus, the explosion could be considered as chemical explosion. From the physical and chemical analysis of the porcelain fragments and the 3D dynamic simulation results of the explosion process, it could be preliminary conclude that an intensive partial discharge in the porcelain bushing leads to the generation of a large amount of thermal energy. Meanwhile, thermal energy leads to the SF<sub>6</sub> gas filled in bushing rapidly decomposing and expanding which generates gas shock waves and resulting in the explosion. The possible reason of explosion accident could be considered as the abnormal discharge existing in porcelain bushing.

**Keywords** Porcelain bushing · Explosion theory · Gas shock wave

---

J. Zhao · Z. Liu · S. Yao  
Inner Mongolia Electric Power Research Institute, Hohhot 010020, China

Y. Yue (✉)  
Inner Mongolia Extra High Voltage Power Supply Corporation, Huhehaote 010012, Neimenggu, China  
e-mail: [hvyue@163.com](mailto:hvyue@163.com)

Y. Yue · L. Yang  
College of Electrical Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710048, China

# 1 Introduction

Tank circuit breaker is a type of circuit breakers, whose arc-extinguishing chamber is in grounded metal box. Meanwhile, as a vital power equipment, tank circuit breaker is widely used in power systems. Bushing is one of the major components of tank circuit breakers, whose main functions include leading high voltage leads inside the equipment to the outside, fixing it, and the components of leads to ground insulation. Furthermore, its safe and stable operation of circuit breaker is related to the safety of the power grid. In 500 kV voltage level system, bushing for tank circuit breaker includes porcelain bushing and composite bushing, whose typical structures are double-shielded structure and single-shielded structure. The double-shielded structure bushing is composed of a pressure equalizing ring, a central conductor, a composite bushing (porcelain bushing), an intermediate shield, a ground shield, and an insulation support. Furthermore, the ground shield is connected to the earth through a metal flange to achieve equipotential to ground. The intermediate shield is made of aluminum material, and it is designed to be suspended in the air. It plays a role of voltage distribution. The main function is to make the electric field between the central conductor and the grounding shield evenly distributed. For the single shield structure, the ground shield exists in while intermediate shielding does not. Although the characteristics of single shielded bushing are simpler structure, easier installation and lower cost, its inner field strength is larger than the double shielded bushing, which is difficult to control. Thus, more accurate design of field strength distribution is required.

On December 17th, 2016, the weather was sunny, and the temperature was below  $-30^{\circ}\text{C}$ . A 500 kV porcelain bushing of tank circuit breaker exploded under the conditions of intact explosion-proof membranes and normal operations. In addition, porcelain fragments were scattered within a range of 60 m, which led damage to a large amount of electrical equipment. Additionally, the safe and stable operation of power grid was affected severely. When the failure occurred, SF<sub>6</sub> low-pressure warning of the fault circuit breaker did not alarmed. Meanwhile, the monitoring system was operating normally. Moreover, from the accident scene, only bushing fragments and some porcelain blocks indicating the presence of ablated glaze could be found. In order to analyze the reasons of the equipment failure, according to the aspects of projectile velocity of the porcelain block, the energy estimation of the porcelain bushing explosion, the porcelain bushing explosion 3D dynamic simulation, porcelain bushing explosion simulation calculation analysis, surface morphology of the porcelain fragmentation, ablation composition analysis, and physicochemical analysis respectively, the research was conducted.

## 2 Data Measurement and Projectile Velocity Calculation of Exploded Porcelain Fragments

In order to conduct a comprehensive explosion reasons analysis of the porcelain bushing, from the perspective of the energy required for the explosion, the porcelain fragments scattered at accident scene with typical characteristics were collected. 14 points were sampled at accident scene in terms of orientation, distance, and fragments mass respectively. Moreover, the parameters of each porcelain fragment are shown in Table 1. From Table 1, it could be seen that the fragment No. 5 is the heaviest that weighs 48.9 kg. Meanwhile, fragment No. 5 is located north of the center of the explosion, whose projectile distance is 28.2 m. Additionally, fragment No. 14 is second heaviest that weighs 35.3 kg. Simultaneously, fragment No. 14 is located at the southeast direction of the explosion center, whose projectile distance is 18.5 m. As Table 1 indicating, five bushing fragments are larger than 10 kg, which are entirely located at the northeast and southeast directions of the center of the explosion. Therefore, it could be inferred that the explosion position of the bushing might at the east side of the bushing. The basic data should be noticed that SF<sub>6</sub> insulation gas with pressure of 0.6 MPa is filled in the porcelain bushing.

Due to the low flying speed of the fragments, the air resistance could be neglected. Meanwhile, because the porcelain bushing is vertical approximately, the projectile angle of exploded fragments is minor, which means that the ejection angle could be considered as horizontal. The height of the explosion bushing is about 6 m referring to the ground. Through measuring the horizontal distance between porcelain

**Table1** Distribution of porcelain fragments at the explosion scene and its related data

Fragments No.	Position (°)	Distance (m)	Mass (kg)	Initial speed (m/s)
1	10	18.0	8.0	16.27
2	20	17.8	27.0	16.09
3	45	18.0	5.5	16.27
4	60	17.9	1.0	16.18
5	90	28.2	48.9	25.48
6	140	29.4	8.5	26.57
7	170	57.9	3.3	52.32
8	195	35.7	7.5	32.26
9	200	32.7	3.0	29.55
10	225	42.0	6.0	37.95
11	250	19.5	9.8	17.62
12	270	28.2	23.6	25.48
13	300	21.3	16.0	19.25
14	315	18.5	35.3	16.72

fragments and explosion point, according to the dynamic equation [1] of the movement of porcelain fragments, it can be obtained that the horizontal initial speed of each porcelain fragment is shown in Table 1. Simultaneously, it could be calculated that the mass weighted average speed is 22.36 m/s. The position is 0° from the east of the center of the explosion. Meanwhile, the measurement direction is rotated counterclockwise.

### 3 Estimation of Explosion Energy of Porcelain Bushing

#### 3.1 Estimation of Chemical Explosion Energy of Porcelain Bushing

According to the Gurney formula [2] of hollow cylinder charge, the quantity of equivalent explosive (equivalent TNT explosive) required for the porcelain bushing to explode is estimated. The Gurney formula is as following.

$$V_0 = \sqrt{2E}(M/C + 0.5)^{1/2} \quad (1)$$

where  $V_0$  is the weighted average initial velocity of the porcelain bottle,  $M$  is the mass of the porcelain bottle with the quantity of 650–850 kg,  $C$  is the mass of the explosive and  $\sqrt{2E}$  is a constant which is selected as 2400 m/s. Thus, the energy required for chemical cracking of porcelain bushing could be obtained. Furthermore, the energy required could be equaled to 55–75 g TNT explosive which has a huge power corresponding to the ordinary grenade. Simultaneously, the corresponding chemical explosion energy range is 251–342 kJ (calculation based on 4200 kJ energy could be released from 1 kg TNT).

#### 3.2 Estimation of Physical Explosion Energy of Porcelain Bushing

According to Ref. [1], the physical explosion of a gas cylinder is a decompression expansion process. During the process, the gas in the cylinder is rapidly reduced from high pressure to atmospheric pressure, which is belongs to the explosion of a permanent gas cylinder. Because the explosion time is rapid, it could be considered that the expansion process is performed under the adiabatic state. Therefore, the explosion energy of permanent gas (physical explosion of porcelain bushing) is the work done when the gas expands, which can be expressed by Eq. (2).

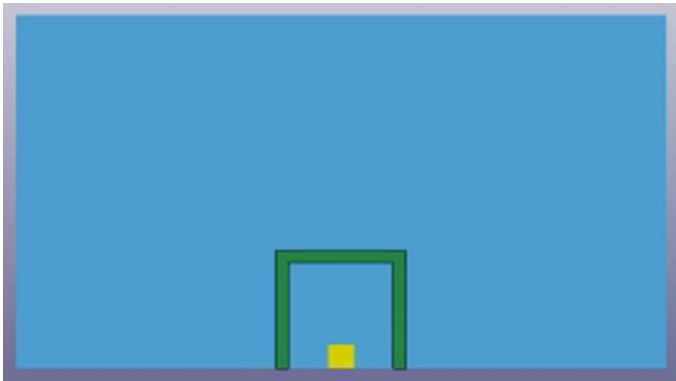
$$E_1 = \frac{10pV}{K-1} \left[ 1 - \left( \frac{1}{10p} \right)^{\frac{K-1}{K}} \right] \times 10^4 \quad (2)$$

where  $E_1$  is the work done  $f$  when the gas expands,  $p$  is the gas pressure,  $V$  is the volume of the porcelain bottle, and  $K$  is the specific heat capacity ratio of  $SF_6$  gas. Substituting  $p = 0.6MPa$ ,  $V = 0.628m^3$  and  $K = 1.095$  into the Eq. (2), the work done by  $SF_6$  gas expansion can be acquired. The physical explosion energy of porcelain bushing equals 57.1 kJ, which is much smaller than the equivalent TNT explosive (between 251 and 342 kJ). Therefore, it can be concluded that the porcelain bushing explosion is not physical explosion filled with high-pressure  $SF_6$  gas, while it should be chemical explosion.

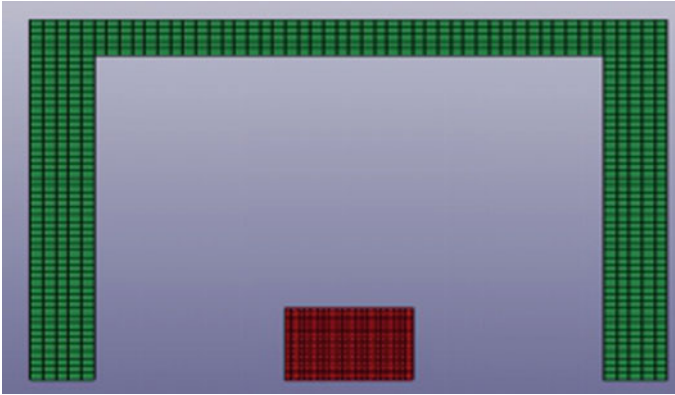
## 4 3D Dynamic Simulation and Simulation Calculation Analysis of Porcelain Bushing Explosion Process

### 4.1 3D Numerical Modelling of the Explosion Process of Porcelain Bushing

Applying the AUTODYN finite element software, the fluid–solid coupling method was implemented to model the destruction process of the porcelain shell under the explosive condition of internal explosives. During the modelling process, Euler’s algorithm was applied by explosives and air (substitute  $SF_6$  gas). Meanwhile, Lagrange’s algorithm was used by porcelain. Through coupling the keywords, axisymmetric models were acquired which are indicated in Figs. 1 and 2.



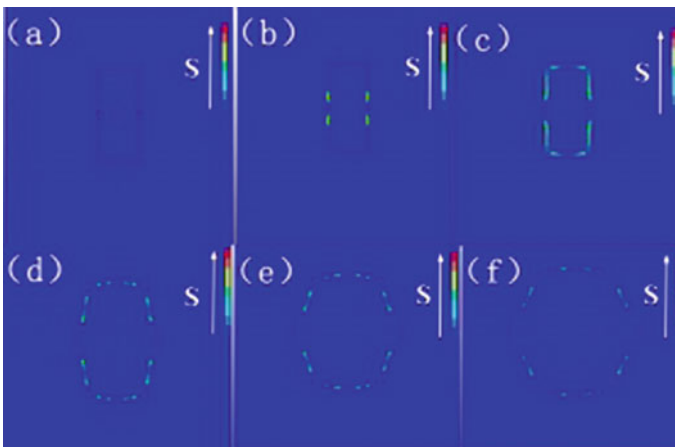
**Fig. 1** Finite element explosion model for simulating explosives



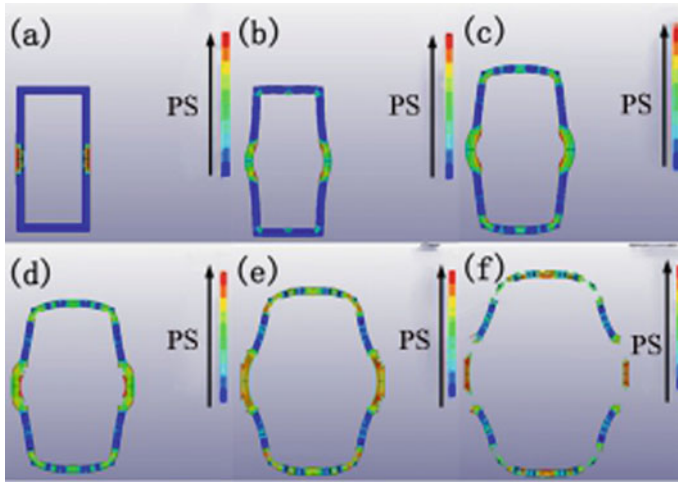
**Fig. 2** Grid model for explosives (red) and porcelain bushing (green)

#### ***4.2 3D Dynamic Simulation and Simulation Calculation Analysis of Porcelain Bushing Explosion Process***

Considering the axisymmetric models in Figs. 1 and 2, excitations were executed to simulate the explosion process of the porcelain bushing. The stress distribution diagram and strain diagram of the porcelain bushing with various explosive time are shown in Fig. 3 and Fig. 4 respectively. The Fig. 3a to f show the stress results at 54  $\mu$ s, 84  $\mu$ s, 230  $\mu$ s, 1300  $\mu$ s, 1800  $\mu$ s and 2200  $\mu$ s respectively. The Fig. 4a to f show the strain distribution at 93  $\mu$ s, 415  $\mu$ s, 1017  $\mu$ s, 1330  $\mu$ s, 1775  $\mu$ s and 2200  $\mu$ s respectively.



**Fig. 3** Stress distribution at different times: **a** 54  $\mu$ s, **b** 84  $\mu$ s, **c** 230  $\mu$ s, **d** 1300  $\mu$ s, **e** 1800  $\mu$ s, **f** 2200  $\mu$ s



**Fig. 4** Plastic strain diagram at different times: **a** 93  $\mu\text{s}$ , **b** 415  $\mu\text{s}$ , **c** 1017  $\mu\text{s}$ , **d** 1330  $\mu\text{s}$ , **e** 1775  $\mu\text{s}$ , **f** 2200  $\mu\text{s}$

From the comparison of Figs. 3b and 4a, it can be seen that the maximum position of the stress and the maximum position of strain is not coincident. In Fig. 3b, it could be found that the pressure at the shell of the porcelain bushing which is closest to the explosion center is zero. However, as corresponding strain diagram shown in Fig. 4a, the stress is the largest and the stress is distributed on the outer surface of the shell. Because the compression wave propagates to the free surface of the shell, the reflection tensile wave is formed, which lead to the tensile stress forming in the shell. From the comparison of Figs. 3f and 4f, it could be seen that the final fracture of the porcelain bushing occurs at the position of superimposed tensile wave. The above analysis indicates that the explosion of porcelain bushing is caused by the tensile stress generated by the shock wave propagating from the explosion to the outer surface of the porcelain bushing, rather than the ordinary gas pressure increasing and expanding.

## 5 Physical and Chemical Analysis of Porcelain Fragments

The Hitachi S-4700 Scanning Electron Microscope (SEM) from Japan was used to analyze the surface morphology of the porcelain fragments. The element composition and content on the surface of the fragments were analyzed by the EDAX energy spectrometer of American AMETEK Company. Meanwhile, the set instrument acceleration voltage is 20 kV.