Power System Restoration with Renewable Participation

Feng Qiu, *Senior Member, IEEE*, Yichen Zhang, *Senior Member, IEEE*, Rui Yao, *Senior Member, IEEE*, Pengwei Du, *Senior Member, IEEE*

Abstract—Power system restoration requires initial power sources to restart generators, energizing transmissions, and pick up critical loads. Sufficient initial power capacity is critical for restoration success and reducing outage duration. Due to the reliability requirement and high standby costs, black-start resources are scarce and expensive in areas where hydro power is not available. Variable renewable energy (VRE), whose fast-ramping capability and economical standby costs are suitable for black-start, is traditionally excluded from participation in system restoration because its uncertainty and variability could cause severe disturbance to the system that is already fragile during restoration. Recently, VRE is becoming a potential participant in system restoration as auxiliary black-start resources. This work will explore the potential benefits of renewable energy in restoration and potential ways for VRE to participate in system restoration. We propose two dispatch models for wind participation. The uncertainty of wind generation is handled by probabilistic constraints to guarantee a feasible restoration plan with a high probability. We perform computational experiments to demonstrate the effectiveness of proposed models and benefits of renewable participation in restoration with the two approaches.

Index Terms—wind dispatchability, data driven, chance constraint, mixed-integer linear program

I. Introduction

Power system resilience has become an important issue in recent years due to the increasing power outages caused by various disruptions. According to the U.S. Energy Information Administration, the observed power outage events, especially the weather-related outages, have increased by 400% from 2000 to 2012 and have incurred $25-70 billion in costs annually [1]. Among all outage-causing weather events, hurricanes and/or tropical storms are the most damaging and widely spread ones, not only in terms of power lost (average 1.3 GW) and the number of customers affected (average 0.8 million), but also in terms of the duration of the outage and the difficulty of restoration. To mitigate the outage damages and reduce the economic and social costs, power systems must be restored to normal as quickly as possible. A typical restoration process is illustrated in Fig. 1, consisting of system

status assessment, system preparation, black-start operations, and load restoration. Note that there are variations depending on the characteristics of a specific power system. Power system restoration has been studied for many decades. However, it remains a challenging topic due to its complexity arising from the combinatorial operations (such as switch operations and start-up sequencing) and technical constraints (such as voltage security).

Fig. 1: Steps in a Typical Restoration Process

The system restoration has been studied from many perspectives. A good estimation of the restoration duration can better prepare the system operators of the electric grid and other dependent critical infrastructures. A probabilistic timing of restoration is proposed in [2]. The restoration can be performed in parallel in different islands of a system. To do this, the sectionalization of the system is important. Ref. [3] proposed a clustering-based network partitioning for parallel power system restoration. A strong formulation for system islanding and restoration was proposed in [4]. The generator start-up problem was studied in [5] and validated by an energization path search algorithm. The decreasing efficiency effect during the start-up procedure was considered in [6]. The model predictive control was employed in optimizing the start-up sequence in [7]. An online generator start-up framework was proposed in [8], where deep learning was used to predict the optimal sequence. Once the generator start-up sequence is determined, an optimal energization path should be calculated for the black-start generators to provide cranking power to non-black-start units. Additionally, a backbone transmission should be formed for online generators to pick up loads. Ref. [9] studied the skeleton-network reconfiguration to build new energization paths using discrete particle swarm optimization. An automatic restoration patch selection based on the power transfer distribution factor was proposed in [10]. A two-stage optimization was employed for recovering the network in [11]. Ref. [12] discussed the optimal skeleton-network restoration while considering generator start-up sequence and load pick-up. Once a backbone network is built with available online

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Power System Restoration M. M. Adibi,2000-06-22 At a time when bulk power systems operate close to their design limits the restructuring of the electric power industry has created vulnerability to potential blackouts Prompt and effective power system restoration is essential for the minimization of downtime and costs to the utility and its customers which mount rapidly after a system blackout Power System Restoration meets the complex challenges that arise from the dynamic capabilities of new technology in areas such as large scale system analysis communication and control data management artificial intelligence and allied disciplines It provides an up to date description of the restoration methodologies and implementation strategies practiced internationally The book opens with a general overview of the restoration process and then covers Techniques used in restoration planning and training Knowledge based systems as operational aids in restoration Issues associated with hydro and thermal power plants High and extra high voltage transmission systems Restoration of distribution systems Power System Restoration is essential reading for all power system planners and operating engineers in the power industry It is also a valuable reference for researchers practicing power engineers and engineering students Sponsored by IEEE Power Engineering Society *Power System Restoration* IEEE Power Engineering Society. Power System Restoration Working Group,1993 *The 37th Annual Conference on Power System and Automation in Chinese Universities (CUS-EPSA)* Pingliang Zeng,Xiao-Ping Zhang,Vladimir Terzija,Yi Ding,Yunxia Luo,2023-04-24 This book includes original peer reviewed research papers from the 37th Annual Conference of Power System and Automation in Chinese Universities CUS EPSA held in Hangzhou China on October 23 25 2022 These papers cover topics as Evolution and development path of the power system Resilience assessment analysis and planning of power system Power system planning and reliability Modelling and simulation of novel power system Power electronic for power system stability analysis Power system relay protection and automation and so on The papers included in this proceedings share the latest research results and practical application examples on the methodologies and algorithms in these areas which makes the book a valuable reference for researchers engineers and university students Modern Power System Analysis Chee-Wooi Ten,Yunhe Hou,2024-03-18 Step into the captivating world of power systems with Modern Power System Analysis Third Edition by acclaimed author Turan G nen and revised and updated by Chee Wooi Ten and Yunhe Hou This illuminating book offers a comprehensive examination of power system analysis Whether you re a curious non specialist a voracious reader seeking knowledge or a librarian or bookseller searching for a valuable resource G nen s masterpiece is sure to captivate you This book is an excellent source to begin your journey An in depth understanding of the concepts and techniques involved in power system analysis is provided in this comprehensive guide The book covers a wide range of topics including fundamental modeling of power transmission networks power flow analysis and fault analysis G nen elucidates the mathematical foundations and computational methods necessary for analyzing and optimizing power systems Readers will gain insights

into advanced topics such as power system harmonics transient stability and power system protection Furthermore the book explores emerging areas like renewable energy integration smart grid technologies and the application of artificial intelligence in power system analysis G nen s meticulous approach combines theoretical explanations practical examples and real world case studies to provide readers with a comprehensive and up to date resource With its focus on modern techniques and advancements this book is an invaluable reference for engineers researchers and students venturing into the exciting realm of power system analysis The text also includes a new chapter on power system restoration which reviews methodologies corresponding to different utilities and practices A cutting edge compilation of the latest developments in power system analysis is presented in this book While the challenges and issues have evolved the text emphasizes the enduring importance of classical methods as the foundation for understanding It integrates today s advancements and addresses contemporary issues and provides readers with a comprehensive grasp of the most current techniques and approaches for analyzing optimizing and managing complex power systems With practical examples real world case studies and a strong focus on emerging areas like renewable energy integration and smart grids this invaluable resource empowers engineers researchers and students to navigate the dynamic landscape of modern power system analysis confidently

Power System Control Under Cascading Failures Kai Sun,Yunhe Hou,Wei Sun,Junjian Qi,2019-01-29 Offers a comprehensive introduction to the issues of control of power systems during cascading outages and restoration process Power System Control Under Cascading Failures offers comprehensive coverage of three major topics related to prevention of cascading power outages in a power transmission grid modelling and analysis system separation and power system restoration The book examines modelling and analysis of cascading failures for reliable and efficient simulation and better understanding of important mechanisms root causes and propagation patterns of failures and power outages Second it covers controlled system separation to mitigate cascading failures addressing key questions such as where when and how to separate Third the text explores optimal system restoration from cascading power outages and blackouts by well designed milestones optimised procedures and emerging techniques The authors noted experts in the field include state of the art methods that are illustrated in detail as well as practical examples that show how to use them to address realistic problems and improve current practices This important resource Contains comprehensive coverage of a focused area of cascading power system outages addressing modelling and analysis system separation and power system restoration Offers a description of theoretical models to analyse outages methods to identify control actions to prevent propagation of outages and restore the system Suggests state of the art methods that are illustrated in detail with hands on examples that address realistic problems to help improve current practices Includes companion website with samples codes and examples to support the text Written for postgraduate students researchers specialists planners and operation engineers from industry Power System Control Under Cascading Failures contains a review of a focused area of cascading power system outages

addresses modelling and analysis system separation and power system restoration **Strategic Planning for Power System Restoration** ,2011 *Advances in Integrated Energy Systems Design, Control and Optimization* Josep M. Guerrero,Amjad Anvari-Moghaddam,2018-03-23 This book is a printed edition of the Special Issue Advances in Integrated Energy Systems Design Control and Optimization that was published in Applied Sciences *Automatic System Restoration for Industrial Power Systems* Anusha Papasani,2021 The power system industry often operates close to its limits to accommodate the increased demand posing a high risk of blackouts Power system restoration techniques are utilized post breakout with the focus on load pickup and speedy recovery In traditional heuristic methods the load is considered to be constant after it is picked However from a system operation point of view the load varies once picked This is commonly observed in industrial loads In Industrial systems loads which involve many induction motors are started in sequence The high starting currents of the induction motors leads to voltage sags that may affect variable speed drives and cause contactors to drop out If the load variation and inrush currents are not considered load at the time of pickup will be significantly underestimated at the time of pickup which might lead to a system re collapse Besides one may have to prioritize the loads to help the operator during restoration An automatic power system restoration tool is developed by using graph theory to provide an efficient restoration path and considers the priority of the loads Cold load pickup CLPU Inrush currents and load variation after picking up for a smooth and successful restoration process Evolution of the smart grid the Intelligent Electronic Device IED has been videployed throughout the power system network for monitoring and control Therefore this dissertation takes advantages on the availability of IEDs to report the loads on the feeder right before the system blackout and the real time load during the system restoration The industrial system and IEEE 30 bus system are used as a test cases to demonstrate the effectiveness of the proposed methodology **Tiet.com-2000.** Surekha Bhanot,2000 **Smart Grid Handbook, 3 Volume Set** ,2016-08-01 Alles Wissenswerte rund um Smart Grids umfassend und interdisziplin r beschrieben von internationalen Experten aus Forschung und Praxis Dieses Buch tr gt dem Wunsch nach einem hochkar tigen Referenzwerk zur Smart Grid Technologie Rechnung eine Technologie die bei der Entwicklung einer umweltfreundlichen Energieinfrastruktur eine zentrale Rolle spielt Das dreib ndige Smart Grid Handbook mit insgesamt 83 Artikeln ist in sechs Abschnitte unterteilt Vision and Drivers Vision und Einflussgr en Transmission bertragung Distribution Verteilung Smart Meters and Customers intelligente Z hler und Kunden Information and Communications Technology Informations und Kommunikationstechnik Socio Economic Issues sozial konomische Aspekte Wichtige Merkmale Geschrieben von einem Team das sich mit Smart Grids auskennt und seine Erfahrung aus den folgenden Bereichen einbringt Forschung Entwicklung Technikeinsatz Standards Branchenpraxis und sozial konomische Aspekte Der Abschnitt Vision and Drivers besch ftigt sich mit Vision Definitionen der Weiterentwicklung und globalen Entwicklung von Smart Grids sowie mit neuen Technologien und Standards Der Abschnitt Transmission erl utert Branchenpraxis Erfahrung im operativen Bereich

Standards Cybersicherheit und Grid Codes Im Abschnitt Distribution werden Verteilungssysteme und Systemkonfigurationen in verschiedenen L ndern sowie verschiedene Lasten die ber das Netz bedient werden vorgestellt Der Abschnitt Smart Meters and Customers untersucht wie Kunden ber Smart Meter mit dem Stromnetz interagieren k nnen *Control and Optimization Methods for Complex System Resilience* Chao Zhai,2023-06-26 This book provides a systematic framework to enhance the ability of complex dynamical systems in risk identification security assessment system protection and recovery with the assistance of advanced control and optimization technologies By treating external disturbances as control inputs optimal control approach is employed to identify disruptive disturbances and online security assessment is conducted with Gaussian process and converse Lyapunov function Model predictive approach and distributed optimization strategy are adopted to protect the complex system against critical contingencies Moreover the reinforcement learning method ensures the efficient restoration of complex systems from severe disruptions This book is meant to be read and studied by researchers and graduates It offers unique insights and practical methodology into designing and analyzing complex dynamical systems for resilience elevation **Advances in Energy Technology** Ramesh C. Bansal,Anshul Agarwal,Vinay Kumar Jadoun,2021-07-27 This book presents select proceedings of International Conference on Energy Material Sciences and Mechanical Engineering EMSME 2020 held at National Institute of Technology Delhi Various topics covered in this book include clean materials solar energy systems wind energy systems power optimization grid integration of renewable energy smart energy storage technologies artificial intelligence in solar and wind system analysis of clean energy material in environment converter topology modelling and simulation This book will be useful for researchers and professionals working in the areas of solar material science electrical engineering and energy technologies **Electrical Transmission Systems and Smart Grids** Miroslav M. Begovic,2012-12-12 Electric transmission networks are among the largest human made engineering systems For example the transmission network in the United States covers over 300 000 km of lines and is served by 500 companies electric utilities In sharp contrast to the very incremental developments of the last century transmission and control technologies experienced a major breakthrough at the beginning of the 21st century The rapid growth of new energy generation technologies renewables significant advances in information processing applied to system monitoring planning operation control and protection radical changes in distribution networks and key shifts in end user behavior advanced metering and control of demand response have combined to produce the modern integrated electrical infrastructure commonly referred to as the smart grid Featuring state of the art peer reviewed entries from the Encyclopedia of Sustainability Science and Technology this book provides a detailed introduction to select key topics which span energy technology engineering and urban planning Worldwide experts discuss the integration of electric energy infrastructure into the broader critical infrastructures of the modern world and their various interdependencies Dedicated chapters cover specific topics ranging from underground transmission and distribution to energy and water interdependence and their

implications for urban areas Coverage also includes the key role of new policy initiatives as catalysts of change *Energy Abstracts for Policy Analysis* ,1988 Knowledge-Based Systems, Four-Volume Set Cornelius T. Leondes,2000-07-11 The design of knowledge systems is finding myriad applications from corporate databases to general decision support in areas as diverse as engineering manufacturing and other industrial processes medicine business and economics In engineering for example knowledge bases can be utilized for reliable electric power system operation In medicine they support complex diagnoses while in business they inform the process of strategic planning Programmed securities trading and the defeat of chess champion Kasparov by IBM s Big Blue are two familiar examples of dedicated knowledge bases in combination with an expert system for decision making With volumes covering Implementation Optimization Computer Techniques and Systems and Applications this comprehensive set constitutes a unique reference source for students practitioners and researchers in computer science engineering and the broad range of applications areas for knowledge based systems **Smart Grid Planning and Implementation** P.E. Gellings,2020-12-22 This book is intended for electric utility managers directors and power system planners regulators and policy makers interested in the steps needed to realize the value of a modern power delivery system This book describes the elements needed in planning and implementing a Smart Grid by outlining how the electricity delivery system can be modernized so it monitors protects and automatically optimizes the operation of its interconnected elements from the central and distributed generator through the high voltage network and distribution system to energy storage installations and to end use consumers and their thermostats electric vehicles appliances and other household devices This comprehensive guide highlights emerging concepts of cyber and physical security resiliency and the newest architecture The Integrated Grid You ll gain an understanding of how a two way flow of electricity and information can be used to create an automated widely distributed energy delivery network **Proceedings of the 7th PURPLE MOUNTAIN FORUM on Smart Grid Protection and Control (PMF2022)** Yusheng Xue,Yuping Zheng,Antonio Gómez-Expósito,2023-02-28 This book includes original peer reviewed research papers from the 7th PURPLE MOUNTAIN FORUM on Smart Grid Protection and Control PMF2022 held in Nanjing China on August 14 15 2022 The accepted papers cover the following topics 1 Advanced power transmission technology2 AC DC hybrid power grid technology3 Power Internet of Things Technology and Application4 Operation control and protection of smart grid5 Active distribution network technology6 Power electronic technology and application7 New technology of substation automation8 Energy storage technology and application9 Application of new technologies such as artificial intelligence blockchain and big data10 Application of Information and Communication Technology11 Low carbon energy planning and security12 Low carbon operation of the power system13 Low carbon energy comprehensive utilization technology14 Carbon trading and power market15 Carbon emission stream and carbon capture technology16 Energy saving and smart energy technology17 Analysis and evaluation of low carbon efficiency of power system18 Carbon flow modelling in power system operationThe papers

included in this proceeding share the latest research results and practical application examples on the methodologies and algorithms in these areas which makes the book a valuable reference for researchers engineers and university students

Renewable Energy Towards Smart Grid Ashwani Kumar,S. C. Srivastava,S. N. Singh,2022-02-28 The book contains select proceedings of the International Conference on Smart Grid Energy Systems and Control SGESC 2021 The proceedings is divided into 03 volumes and this volume focuses on renewable energy towards the smart grid It includes papers related to smart grid renewable energy its integration and DERs in the network for better energy management and ancillary services The book presents cutting edge research in the emerging fields of micro nano and smart devices and systems from experts Most of the contributors have built devices or systems or developed processes or algorithms in these areas This book is a unique collection of chapters from different areas with a common theme and will be immensely useful to academic researchers and practitioners in the industry   **Machine Learning and Its Applications** Georgios Paliouras,Vangelis Karkaletsis,Constantine D. Spyropoulos,2003-06-29 In recent years machine learning has made its way from artificial intelligence into areas of administration commerce and industry Data mining is perhaps the most widely known demonstration of this migration complemented by less publicized applications of machine learning like adaptive systems in industry financial prediction medical diagnosis and the construction of user profiles for Web browsers This book presents the capabilities of machine learning methods and ideas on how these methods could be used to solve real world problems The first ten chapters assess the current state of the art of machine learning from symbolic concept learning and conceptual clustering to case based reasoning neural networks and genetic algorithms The second part introduces the reader to innovative applications of ML techniques in fields such as data mining knowledge discovery human language technology user modeling data analysis discovery science agent technology finance etc   *Computational Advancement in Communication Circuits and Systems* Koushik Maharatna,Maitreyi Ray Kanjilal,Sukumar Chandra Konar,Sumit Nandi,Kunal Das,2019-07-25 This book gathers the proceedings of the International Conference on Computational Advancement in Communication Circuits and Systems ICCACCS 2018 which was organized by Narula Institute of Technology under the patronage of the JIS group affiliated with West Bengal University of Technology The book presents peer reviewed papers that highlight new theoretical and experimental findings in the fields of electronics and communication engineering including interdisciplinary areas like Advanced Computing Pattern Recognition and Analysis and Signal and Image Processing The respective papers cover a broad range of principles techniques and applications in microwave devices communication and networking signal and image processing computations and mathematics and control The proceedings reflect the conference s strong emphasis on methodological approaches and focus on applications within the domain of Computational Advancement in Communication Circuits andSystems They also address emerging technologies in electronics and communication together with the latest practices issues and trends

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Table of Contents Power System Restoration

1. Understanding the eBook Power System Restoration
   - The Rise of Digital Reading Power System Restoration
   - Advantages of eBooks Over Traditional Books
2. Identifying Power System Restoration
   - Exploring Different Genres
   - Considering Fiction vs. Non-Fiction
   - Determining Your Reading Goals
3. Choosing the Right eBook Platform
   - Popular eBook Platforms
   - Features to Look for in an Power System Restoration
   - User-Friendly Interface
4. Exploring eBook Recommendations from Power System Restoration
   - Personalized Recommendations
   - Power System Restoration User Reviews and Ratings
   - Power System Restoration and Bestseller Lists
5. Accessing Power System Restoration Free and Paid eBooks
   - Power System Restoration Public Domain eBooks

14. Embracing eBook Trends
     - Integration of Multimedia Elements
     - Interactive and Gamified eBooks

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