Distribution System Optimization to Manage Distributed Energy Resources (DERs) for Grid Services

Other titles in Foundations and Trends® in Electric Energy Systems

Peer-to-Peer Energy Sharing: A Comprehensive Review
Wayes Tushar, Sohrab Nizami, M. Imran Azim, Chau Yuen, David B. Smith, Tapan Saha and H. Vincent Poor
ISBN: 978-1-63828-156-6

LLC Resonant Converters: An Overview of Modeling, Control and Design Methods and Challenges
Claudio Adragna
ISBN: 978-1-63828-066-8

The Role of Power Electronics in Modern Energy System Integration
Saeed Peyghami, Subham Sahoo, Huai Wang, Xiongfei Wang and Frede Blaabjerg
ISBN: 978-1-63828-008-8

Cyber–Physical System Security of Distribution Systems
Chen-Ching Liu, Juan C. Bedoya, Nitasha Sahani, Alexandru Stefanov, Jennifer Appiah-Kubi, Chih-Che Sun, Jin Young Lee and Ruoxi Zhu
ISBN: 978-1-68083-852-7

Network-Based Analysis of Rotor Angle Stability of Power Systems
Yue Song, David J. Hill and Tao Liu
ISBN: 978-1-68083-778-0

Distribution System Optimization to Manage Distributed Energy Resources (DERs) for Grid Services

Anamika Dubey
Washington State University
anamika.dubey@wsu.edu

Sumit Paudyal
Florida International University
spaudyal@fiu.edu

now
the essence of knowledge
Boston — Delft

Full text available at: http://dx.doi.org/10.1561/3100000030

Foundations and Trends® in Electric Energy Systems

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

A. Dubey and S. Paudyal. *Distribution System Optimization to Manage Distributed Energy Resources (DERs) for Grid Services*. Foundations and Trends® in Electric Energy Systems, vol. 6, no. 3-4, pp. 120–264, 2023.

ISBN: 978-1-63828-189-4
© 2023 A. Dubey and S. Paudyal

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, mechanical, photocopying, recording or otherwise, without prior written permission of the publishers.

Photocopying. In the USA: This journal is registered at the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923. Authorization to photocopy items for internal or personal use, or the internal or personal use of specific clients, is granted by now Publishers Inc for users registered with the Copyright Clearance Center (CCC). The 'services' for users can be found on the internet at: www.copyright.com

For those organizations that have been granted a photocopy license, a separate system of payment has been arranged. Authorization does not extend to other kinds of copying, such as that for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale. In the rest of the world: Permission to photocopy must be obtained from the copyright owner. Please apply to now Publishers Inc., PO Box 1024, Hanover, MA 02339, USA; Tel. +1 781 871 0245; www.nowpublishers.com; sales@nowpublishers.com

now Publishers Inc. has an exclusive license to publish this material worldwide. Permission to use this content must be obtained from the copyright license holder. Please apply to now Publishers, PO Box 179, 2600 AD Delft, The Netherlands, www.nowpublishers.com; e-mail: sales@nowpublishers.com

Foundations and Trends® in Electric Energy Systems

Volume 6, Issue 3-4, 2023

Editorial Board

Editorial Scope

Topics

Foundations and Trends® in Electric Energy Systems publishes survey and tutorial articles in the following topics:

- Advances in power dispatch
- Demand-side and grid scale data analytics
- Design and optimization of electric services
- Distributed control and optimization of distribution networks
- Distributed sensing for the grid
- Distribution systems
- Fault location and service restoration
- Integration of physics-based and data-driven modeling of future electric energy systems
- Integration of Power electronics, Networked FACTS
- Integration of renewable energy sources
- Interdependence of power system operations and planning and the electricity markets
- Microgrids
- Modern grid architecture
- Power system analysis and computing
- Power system dynamics
- Power system operation
- Power system planning
- Power system reliability
- Power system transients
- Security and privacy
- Stability and control for the whole multi-layer (granulated) network with new load models (to include storage, DR, EVs) and new generation
- System protection and control
- The new stability guidelines and control structures for supporting high penetration of renewables (>50%)
- Uncertainty quantification for the grid
- System impacts of HVDC

Information for Librarians

Foundations and Trends® in Electric Energy Systems, 2023, Volume 6, 4 issues. ISSN paper version 2332-6557. ISSN online version 2332-6565. Also available as a combined paper and online subscription.

Contents

Distribution System Optimization to Manage Distributed Energy Resources (DERs) for Grid Services

Anamika Dubey[1] and Sumit Paudyal[2]

[1] *Washington State University, USA; anamika.dubey@wsu.edu*
[2] *Florida International University, USA; spaudyal@fiu.edu*

ABSTRACT

The proliferation of distributed energy resources (DERs) and the deployment of advanced sensing and control technologies in electric power distribution systems calls for coordinated management of the grid's resources. This has sparked a growing interest in optimization methods for large-scale unbalanced power distribution systems, with the goal of improving grid's operational efficiency and resilience. The current fast-paced research in this domain is driven by the challenging mathematical problem of three-phase optimal power flow (OPF). This monograph introduces the state-of-the-art optimization methods applied to unbalanced power distribution systems for the provisioning of grid services from DERs. To that end, fundamentals of D-OPF methods are introduced along with the unique challenges and differences compared to the bulk grid and related aspects of computational complexity due to mutual coupling, unbalanced loading conditions, and control of legacy devices. Different models for formulating D-OPF problems are described in

---

Anamika Dubey and Sumit Paudyal (2023), "Distribution System Optimization to Manage Distributed Energy Resources (DERs) for Grid Services", Foundations and Trends® in Electric Energy Systems: Vol. 6, No. 3-4, pp 120–264. DOI: 10.1561/3100000030.

detail, as are methods for relaxing or approximating the formulations to achieve computational tractability. Finally, the use of D-OPF formulations to solve distribution-level operational problems via advanced distribution-level applications is described in detail. The specific applications discussed in this monograph include: (1) Volt-VAR control and Conservation Voltage Reduction using legacy voltage control devices and DERs, and (2) Solutions for Tomorrow's Grid Reconfiguration and Restoration using DERs.

1

Introduction

With the integration of numerous actionable agents, distributed generation resources, and sensing devices, the electric power distribution system is rapidly evolving into an autonomous and intelligent system. For example, behind-the-meter photovoltaic (PV) output has reached 71.3 GW in the U.S. power grid, with over 2.5 million PV panels installed. Likewise, a recent study shows California's fleet of light-duty plug-in EVs could double the total transportation electricity demand, from under 5,000 GWh in 2019 to over 10,000 GWh by 2030. Simultaneously, the grid is also getting overwhelmed with extreme weather events that are happening at a higher frequency and causing greater damage. Recent fire-related damages and fatalities caused by high-voltage transmission lines combined with dry weather are costing billions of dollars each year, with the only practical solution being de-energizing the lines and disrupting the power supply to millions of customers. The recent advances in the distribution systems, including the integration of distributed generation (DGs), distributed energy resources (DERs), and microgrids provide potential means to improve the grid's operational resilience. An advanced decision-support system is needed to plan and manage grid operations by proactively managing the grid's variable, uncertain, and distributed resources. Consequently, resilient operational solutions for power distribution grids have drawn significant attention. These applications range from leveraging recent advances in smart grid technology, such as remote control capabilities and DERs, to enable advanced grid services such as frequency and voltage support for the bulk grid and resilient operations through intentional islanding to support critical services during disruptions.

The need for advanced grid support functionality from a large number of DERs has sparked increased interest in optimization methods for large-scale unbalanced power distribution systems. This monograph provides a much-needed primer on optimization methods used in active power distribution systems for advanced operations, with the goal of benefiting researchers working in this field. The graduate students and young researchers working in the area of DERs and distribution systems operations need a background on not only topics related to power distribution engineering but also a wide variety of interdisciplinary subjects to address the upcoming challenges. The monograph will benefit a diverse pool of researchers and industry practitioners by building the necessary background on modeling the distribution systems (with DERs) and system optimization methods for provisioning grid services.

Specifically, we introduce the state-of-the-art optimization methods applied to unbalanced power distribution systems for the provisioning of grid services for efficient and resilient grid operations. We begin with mathematical descriptions of the unbalanced power flow and optimal power flow (OPF) models and describe a systematic approach to problem formulation using an example test feeder. Our discussion also includes a mathematical description of distribution system components and controllable devices. We describe the mathematical complexity of resulting optimization problems and introduce commonly used relaxation and approximation techniques for computational tractability. We also detail the limitations of the existing formulations. The mathematical formulations are complemented by open-source codes using example distribution systems. Following that, we will describe the problem formulation for multiple grid service application cases that use distribution OPF. These algorithms are tested with large-scale distribution test systems, and the implications of using DGs/DERs for specific grid services are discussed. Finally, we summarize outstanding challenges and the need for additional research in this area.

1.1 Motivation for Optimizing Distribution Systems Operations

The utility distribution systems are designed to deliver reliable electric power economically to the electrical consumers at their place of consumption. However, over the last decade, the electric power grid has been transforming unprecedentedly, necessitating a significant change in how we design, operate, and control traditional power systems. Starting with the high penetration of DERs, the integration of electric vehicles (EVs), bi-directional power flow, and smart metering, the power grid, as we know, is changing. The inherent variability of renewable generation and the vulnerability of traditional power systems to the demand and generation stochasticity can potentially result in system-level problems. However, if deployed and controlled purposefully, these new technologies can provide multiple crucial grid services that can help improve the efficiency, reliability, and resilience of the power grid.

Historically, distribution system operations have been mostly passive, with rule-based methods primarily used to control the feeder's few legacy voltage control devices, such as capacitor banks and voltage regulators. These control rules were pre-designed and acted based on local measurements. Since the loads were predictable and the system lacked any local generation resources, the rule-based controls were sufficient to ensure desirable system operations. However, the integration of DERs led to added variability and uncertainty in distribution system operations rendering rule-based and local-control-only algorithms inapplicable. Multiple studies showed that the integration of active grid-edge resources such as photovoltaic generation (PVs) or new load types, such as EVs may lead to multiple system-level challenges, including, but not limited to, voltage limit violations (overvoltages/undervolatges), increased voltage variability and three-phase voltage unbalance, and thermal limit violations [42]–[44], [88], [137]. It was also shown that the local control might result in unnecessary tap changes and capacitor bank operations; these are mechanical devices, and a higher number of operations can lead to mechanical failures [1]. Mitigating these system-level operational challenges requires a coordinated operation of systems' controllable devices, including the new resources. It was also recognized that the new grid-edge resources could provide additional grid services, such as capacity, flexibility, ramping, voltage support, and so on, that were previously not possible in a passive power distribution system. This resulted in the development of new methods and advanced applications to actively manage grid-edge resources [41].

With the evolution of active power distribution systems and new grid requirements, optimal power flow (OPF) methods emerged as a potential mechanism to optimize distribution system operations for different grid service requirements. A comprehensive review of OPF methods is provided in the following articles [26], [63], [95], [97]. When compared to the bulk power grid, distribution-level OPF (D-OPF) presents distinct challenges due to three-phase unbalanced loading, mutual coupling among the different phases of the line, the presence of single-phase and two-phase branches, and radial topology with a high R/X ratio, which causes significant voltage drops. Furthermore, grid-edge optimization necessitates the integration of various technologies such as battery storage, smart inverters, capacitor banks, voltage regulators, and secondary voltage controllers resulting in mixed-integer decision variables and inter-temporal constraints. Besides that, distribution-level optimization necessitates the inclusion of multiple sources of uncertainty from model and measurement data, resulting in computationally intractable stochastic optimization formulations. As a result, D-OPF formulations and approaches require separate consideration than bulk-grid models.

1.2 DGs/DERs for Grid Services and D-OPF Formulations

In this section, we identify the commonly discussed grid services that DERs could potentially provide. These services are identified as those that originated for the distribution system or for the bulk-grid level. We also identify the possible class of objective functions associated with each grid service, controllable devices, and DER control variables, see Table 1.1. It is worth noting that many of these DER-enabled grid services are currently being validated through field demonstrations or are in the process of being deployed in the field, see [5], [6], [40], [78],

Table 1.1: Grid Services from DGs/DERs that can benefit from Distribution Optimal Power Flow Models and Algorithms

Grid Services	Problem Objective	Controllable Devices
Improved support for voltage and power quality	Manage feeder voltages (magnitude, variability, unbalance), reduce losses	Voltage regulators, capacitor banks, DG active/reactive power
Network congestion management service	Manage network thermal limit constraints via network reconfiguration, network tariff design and flexibility procurement	Tie switches, sectionalizing switches, Building energy management system (BMS), active/reactives power from DGs and other DERs (BESS, EVs)
Avoided or deferred distribution capacity costs	Conservation voltage reduction, reduce system peak, manage system constraints	DG active/reactive power from DGs and other DERs (BESS, EVs), voltage control devices
Leverage demand response capability	Reduce system peak Manage system constraints	Building energy management system (BMS), active power from DGs and other DERs (BESS, EVs)
Reduce wholesale energy costs	Distribution market to optimize social welfare cost	
Reliability via DG-assisted restoration	Reduce outage duration	Tie switches, sectionalizing switches, grid-forming DGs, microgrids
Resilience via Intentional Islanding	Reduce outage duration, Stable islands	
Ancillary service (Bulk-grid frequency support)	Active power control for frequency support	Active power support from DGs and other DERs (BESS, EVs, BMS)
Ancillary service (Bulk-grid voltage support)	Reactive power control for voltage support	Reactive power support from DGs and other DERs (BESS, EVs, BMS)
Black-start regulation	Reduce system peak, Manage system constraint	Grid forming DERs
Flexibility reserve	Manage renewable variability	BESS, BMS, EVs
Energy and Ancillary service markets	Generate revenue by market participation	BESS, BMS, EVs

[143]. The procurement of these grid services can be formulated as an OPF problem with a specified objective function and constraints. The optimization problem type is dictated by control variables, the optimization time horizon, and the problem objective. Some grid services, such as bulk grid frequency and voltage support, may require a closed-loop formulation instead of an open-loop OPF model. Additionally, the problem formulation may involve multiple decision-making

hierarchies, such as coordinating distribution-level markets with wholesale markets. Although such applications can be modeled as one large optimization problem, they require hierarchical or distributed optimization approaches to manage the resulting computational complexity and information and data privacy requirements.

Mathematically, D-OPF is a constrained optimization problem. In its most general form, this results in a nonlinear mixed-integer optimization problem. However, several versions of the general model are solved depending on the decision variables and power flow models used in the problem definition [67]. A nonlinear D-OPF formulation is often solved where only continuous decision variables are modeled, excluding any discrete control devices in the formulation. These models can use bus-injection or branch-flow power flow models, resulting in different D-OPF formulations. In this case, the primary source of nonlinearity is due to nonlinear power flow equations. Given the difficulty of solving nonlinear optimization problems, power flow equations can be approximated or relaxed to produce a simpler linear or convex optimization formulations. Real-world D-OPF problems often require optimizing for both discrete and continuous control variables, resulting in a mixed-integer nonlinear optimization problem. These are some of the most difficult optimization problems to solve.

A list of problem types is described in Table 1.2. The control variables and optimization horizon will define the problem type. DG control parameters, such as active and reactive power dispatch from DGs, are modeled as continuous variables. However, integers, especially binary variables, are often included to model the connectivity/availability statuses of DG/DER devices; for example, the on/off status of EV charging, and the charge/discharge status of BESS are modeled as binary variables. Likewise, tap settings for voltage regulators and capacitor bank switch status are modeled as discrete decisions. The optimization time horizon is defined by the type of controllable device and whether they result in inter-temporal constraints. For example, the state-of-charge for BESS at future time intervals is a function of the current decision requiring a multi-time period optimization formulation. On the contrary, the reactive power dispatch from smart inverters connected to PVs does not carry any memory for the next time step and hence a single-

Table 1.2: Taxonomy of D-OPF Problem Types

D-OPF type	Power flow model	Optimization model	Decision variables
Nonlinear models	Bus-injection model [26]	NLP	Continuous
	Branch flow model [10], [11]	NLP	
Linear Approximate model	Lin-dist flow [46], [50]	LP	Continuous
	Other linearized models [58], [68], [127], [141]	LP	
Convex Relaxation models	Semi-definite relaxation [8], [46]	SDP	Continuous
	Second-order cone relaxation [46], [65], [68]	SOCP	
Mixed-integer models	Nonlinear power flow model [108], [148]	MINLP	Continuous, discrete
	Linear approximate model [99], [128]	MILP	
	Convex relaxation [4], [129], [134], [153]	MISOCP, MISDP	

period optimization will suffice. A stochastic optimization problem can be considered when it is important to incorporate uncertainty in the model parameters and measurements.

Table 1.3 details the controllable devices at the distribution level, corresponding controllable variables, and their types. Distribution systems primarily include legacy voltage control devices such as capacitor banks and voltage regulators, and feeder-level switches. Active distribution systems are integrated with various DER technologies, including PVs, BESS, EVs, BMS, etc. In the past decade, several power-electronics-based devices have also emerged as a viable option to control voltage and power flow in the distribution systems [13], [73], [91], [107]. Some examples include Low-voltage Distribution Static Compensator (D-STATCOM) [105], Static Var Compensator (SVC) [106], Unified power flow controller (UPFC) [33], [104], and Soft open points [70].

Table 1.3: Distribution-level Controllable Devices

Controllable Device	Controllable Parameter	Decision Variable
Voltage regulator	Tap setting	Discrete
Capacitor bank	On/Off status	Discrete
Feeder Switches	Connect/disconnect	Discrete
PVs with smart inverters	Active and/or reactive power	Continuous
	Connect/disconnect	Discrete
BESS with smart inverters	Active and/or reactive power	Continuous
	Charge/discharge status	Discrete
EVs	Active power	Continuous
	Charge/discharge	Discrete
BMS	Active power setpoints	Continuous
Other DGs (grid-following)	Active and/or reactive power	Continuous
	Connect/disconnect	Discrete
Other DGs (grid-forming)	Voltage and frequency	Continuous
	Connect/disconnect	Discrete
	Other Power Electronics Devices	
Low-voltage Distribution STATCOM	Reactive power	Continuous
Unified power flow controller	Voltage and reactive power	Continuous
	Mode of operation	Discrete
Static Var Compensator (SVC)	Capacitor stages	Discrete
Soft Open Point (back-to-back VSCs, multiterminal VSCs)	Active and reactive power flow	Continuous

1.3 Organization of Monograph

The monograph is organized as follows. Section 1 introduces the concept of active power distribution systems, motivates the optimization for grid services, and describes the taxonomy for distribution-level optimization problems. Section 2 briefly reviews the distribution systems network and DER models for quasi-static analysis and optimization, including the distribution power flow models and algorithms. Section 3 develops the analytical framework for modeling distribution optimal power flow problems and introduces different approximation and relaxation techniques for scalability. Section 4 introduces discrete decisions into the distribution-level optimization problems and develops different mixed-integer distribution optimal power flow models. Section 5 develops application cases for distribution-level services using DERs under normal operating conditions, namely services for voltage optimization. This section uses different OPF models introduced in Sections 3 and 4. Section 6 develops multiple application cases for resilient distribution systems operations using DERs in active power distribution systems. Section 7 presents some concluding remarks and future research directions.

References

[1] Y. P. Agalgaonkar, B. C. Pal, and R. A. Jabr, "Distribution voltage control considering the impact of pv generation on tap changers and autonomous regulators," *IEEE Transactions on Power Systems*, vol. 29, no. 1, 2014, pp. 182–192. DOI: 10.1109/TPWRS.2013.2279721.

[2] H. Ahmadi and J. R. Martı, "Linear current flow equations with application to distribution systems reconfiguration," *IEEE Transactions on Power Systems*, vol. 30, no. 4, 2015, pp. 2073–2080.

[3] I. Alsaleh, L. Fan, and M. Ma, "Mixed-integer sdp relaxation-based volt/var optimization for unbalanced distribution systems," in *2019 IEEE Power Energy Society General Meeting (PESGM)*, pp. 1–5, 2019.

[4] I. Alsaleh and L. Fan, "Multi-time co-optimization of voltage regulators and photovoltaics in unbalanced distribution systems," *IEEE Transactions on Sustainable Energy*, vol. 12, no. 1, 2021, pp. 482–491. DOI: 10.1109/TSTE.2020.3007045.

[5] K. B. Ardani, E. O'Shaughnessy, and P. D. Schwabe, "Coordinating distributed energy resources for grid services: A case study of pacific gas and electric," 2018.

[6] Australia's OpEN project, *Open Energy Networks, An Energy Networks Australia and AEMO joint project*, 2022. URL: https://www.energynetworks.com.au/projects/open-energy-networks/#open-reports-and-publications.

[7] X. Bai and H. Wei, "Semi-definite programming-based method for security-constrained unit commitment with operational and optimal power flow constraints," *IET Generation, Transmission Distribution*, vol. 3, no. 2, Feb. 2009, pp. 182–197. DOI: 10.1049/iet-gtd:20070516.

[8] X. Bai, H. Wei, K. Fujisawa, and Y. Wang, "Semidefinite programming for optimal power flow problems," *International Journal of Electrical Power & Energy Systems*, vol. 30, no. 6, 2008, pp. 383–392. URL: https://www.sciencedirect.com/science/article/pii/S0142061507001378.

[9] R. Baldick, B. H. Kim, C. Chase, and Y. Luo, "A Fast Distributed Implementation of Optimal Power Flow," *IEEE Transactions on Power Systems*, vol. 14, no. 3, 1999, pp. 858–864. DOI: 10.1109/59.780896.

[10] M. Baran and F. F. Wu, "Optimal sizing of capacitors placed on a radial distribution system," *IEEE Transactions on Power Delivery*, vol. 4, no. 1, 1989, pp. 735–743.

[11] M. Baran and F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Transactions on Power Delivery*, vol. 4, no. 2, 1989, pp. 1401–1407. DOI: 10.1109/61.25627.

[12] M. E. Baran and M.-Y. Hsu, "Volt/var control at distribution substations," *IEEE Transactions on Power Systems*, vol. 14, no. 1, 1999, pp. 312–318.

[13] A. K. Barnes, V. Martinelli, and J. Simonelli, "A local voltage regulator that improves energy savings under advanced volt-var control," in *2014 IEEE PES T&D Conference and Exposition*, pp. 1–5, 2014. DOI: 10.1109/TDC.2014.6863259.

[14] N. Bastianello, A. Ajalloeian, and E. Dall'Anese, "Distributed and inexact proximal gradient method for online convex optimization," *arXiv preprint arXiv:2001.00870*, 2020.

[15] M. Bazrafshan, N. Gatsis, and H. Zhu, "Optimal power flow with step-voltage regulators in multi-phase distribution networks," *IEEE Transactions on Power Systems*, vol. 34, no. 6, 2019, pp. 4228–4239.

[16] M. Bazrafshan and N. Gatsis, "Comprehensive modeling of three-phase distribution systems via the bus admittance matrix," *IEEE Transactions on Power Systems*, vol. 33, no. 2, 2017, pp. 2015–2029.

[17] A. Bernstein, C. Wang, E. Dall'Anese, J. Le Boudec, and C. Zhao, "Load flow in multiphase distribution networks: Existence, uniqueness, non-singularity and linear models," *IEEE Transactions on Power Systems*, vol. 33, no. 6, 2018, pp. 5832–5843. DOI: 10.1109/TPWRS.2018.2823277.

[18] A. Bernstein and E. Dall'Anese, "Linear power-flow models in multiphase distribution networks," in *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, IEEE, pp. 1–6, 2017.

[19] A. Bernstein and E. Dall'Anese, "Real-time feedback-based optimization of distribution grids: A unified approach," *IEEE Transactions on Control of Network Systems*, vol. 6, no. 3, 2019, pp. 1197–1209.

[20] A. Bokhari, A. Alkan, R. Dogan, M. Diaz-Aguiló, F. de León, D. Czarkowski, Z. Zabar, L. Birenbaum, A. Noel, and R. E. Uosef, "Experimental determination of the ZIP coefficients for modern residential, commercial, and industrial loads," *IEEE Transactions on Power Delivery*, vol. 29, no. 3, Jun. 2014, pp. 1372–1381. DOI: 10.1109/TPWRD.2013.2285096.

[21] A. Bokhari, A. Raza, M. Diaz-Aguiló, F. de León, D. Czarkowski, R. E. Uosef, and D. Wang, "Combined effect of CVR and DG penetration in the voltage profile of low-voltage secondary distribution networks," *IEEE Transactions on Power Delivery*, vol. 31, no. 1, Feb. 2016, pp. 286–293. DOI: 10.1109/TPWRD.2015.2422308.

[22] S. Bolognani and S. Zampieri, "On the existence and linear approximation of the power flow solution in power distribution networks," *IEEE Transactions on Power Systems*, vol. 31, no. 1, Jan. 2016, pp. 163–172. DOI: 10.1109/TPWRS.2015.2395452.

[23] S. Bolognani and F. Dörfler, "Fast power system analysis via implicit linearization of the power flow manifold," in *2015 53rd Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, IEEE, pp. 402–409, 2015.

[24] S. Boyd, N. Parikh, E. Chu, B. Peleato, and J. Eckstein, "Distributed optimization and statistical learning via the alternating direction method of multipliers," *Foundations and Trends® in Machine Learning*, vol. 3, no. 1, 2011, pp. 1–122. DOI: 10.1561/2200000016.

[25] S. Bruno, S. Lamonaca, G. Rotondo, U. Stecchi, and M. La Scala, "Unbalanced three-phase optimal power flow for smart grids," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, 2011, pp. 4504–4513. DOI: 10.1109/TIE.2011.2106099.

[26] M. B. Cain, R. P. O'neill, A. Castillo, *et al.*, "History of Optimal Power Flow and Formulations," *Federal Energy Regulatory Commission*, vol. 1, 2012, pp. 1–36.

[27] D. Cao, W. Hu, J. Zhao, Q. Huang, Z. Chen, and F. Blaabjerg, "A multi-agent deep reinforcement learning based voltage regulation using coordinated pv inverters," *IEEE Transactions on Power Systems*, vol. 35, no. 5, 2020, pp. 4120–4123.

[28] D. Cao, J. Zhao, W. Hu, F. Ding, Q. Huang, Z. Chen, and F. Blaabjerg, "Data-driven multi-agent deep reinforcement learning for distribution system decentralized voltage control with high penetration of pvs," *IEEE Transactions on Smart Grid*, 2021.

[29] A. Castillo and D. F. Gayme, "Grid-scale energy storage applications in renewable energy integration: A survey," *Energy Conversion and Management*, vol. 87, 2014, pp. 885–894.

[30] A. Castillo, P. Lipka, J.-P. Watson, S. S. Oren, and R. P. O'Neill, "A successive linear programming approach to solving the IV-ACOPF," *IEEE Transactions on Power Systems*, vol. 31, no. 4, 2016, pp. 2752–2763.

[31] Y. Chen and B. Zhang, "Learning to solve network flow problems via neural decoding," *arXiv preprint arXiv:2002.04091*, 2020.

[32] S. Ciraci, J. Daily, J. Fuller, A. Fisher, L. Marinovici, and K. Agarwal, "Fncs: A framework for power system and communication networks co-simulation," in *Proceedings of the symposium on theory of modeling & simulation-DEVS integrative*, pp. 1–8, 2014.

[33] D. Montenegro, J. Taylor, and R. Dugan, "Open source unified power flow controller model for quasi-static time series simulation," *in Proc. CIGRE U.S. Nat. Committee, Grid Future Symposium, Philadelphia, PA, USA*, Nov. 2016.

[34] E. Dall'Anese, H. Zhu, and G. B. Giannakis, "Distributed optimal power flow for smart microgrids," *IEEE Transactions on Smart Grid*, vol. 4, no. 3, 2013, pp. 1464–1475. DOI: 10.1109/TSG.2013.2248175.

[35] E. Dall'Anese, S. V. Dhople, B. B. Johnson, and G. B. Giannakis, "Decentralized optimal dispatch of photovoltaic inverters in residential distribution systems," *IEEE Transactions on Energy Conversion*, vol. 29, no. 4, Dec. 2014, pp. 957–967. DOI: 10.1109/TEC.2014.2357997.

[36] N. Daratha, B. Das, and J. Sharma, "Coordination between oltc and svc for voltage regulation in unbalanced distribution system distributed generation," *IEEE Transactions on Power Systems*, vol. 29, no. 1, 2014, pp. 289–299.

[37] S. V. Dhople, S. S. Guggilam, and Y. C. Chen, "Linear approximations to ac power flow in rectangular coordinates," in *2015 53rd Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, pp. 211–217, 2015. DOI: 10.1109/ALLERTON.2015.7447006.

[38] R. Diao, Z. Wang, D. Shi, Q. Chang, J. Duan, and X. Zhang, "Autonomous voltage control for grid operation using deep reinforcement learning," in *2019 IEEE Power & Energy Society General Meeting (PESGM)*, IEEE, pp. 1–5, 2019.

[39] Docker, *Docker—Build, Ship and Run Any App, Anywhere. Docker Inc., San Francisco, CA, USA*. 2018.

[40] W. Driscoll. (2018). "U.S. utilities test distributed energy management," URL: https://pv-magazine-usa.com/2018/12/14/u-s-utilities-test-distributed-energy-management/ (accessed on 03/03/2023).

[41] A. Dubey, A. Bose, M. Liu, and L. N. Ochoa, "Paving the way for advanced distribution management systems applications: Making the most of models and data," *IEEE Power and Energy Magazine*, vol. 18, no. 1, 2020, pp. 63–75.

[42] A. Dubey and S. Santoso, "Electric vehicle charging on residential distribution systems: Impacts and mitigations," *IEEE Access*, vol. 3, 2015, pp. 1871–1893. DOI: 10.1109/ACCESS.2015.2476996.

[43] A. Dubey and S. Santoso, "On estimation and sensitivity analysis of distribution circuit's photovoltaic hosting capacity," *IEEE Transactions on Power Systems*, vol. 32, no. 4, 2017, pp. 2779–2789. DOI: 10.1109/TPWRS.2016.2622286.

[44] A. Dubey, S. Santoso, and A. Maitra, "Understanding photovoltaic hosting capacity of distribution circuits," in *2015 IEEE Power & Energy Society General Meeting*, pp. 1–5, 2015. DOI: 10.1109/PESGM.2015.7286510.

[45] R. El Helou, D. Kalathil, and L. Xie, "Fully decentralized reinforcement learning-based control of photovoltaics in distribution grids for joint provision of real and reactive power," *IEEE Open Access Journal of Power and Energy*, vol. 8, 2021, pp. 175–185.

[46] M. Farivar and S. H. Low, "Branch flow model: Relaxations and convexification: Part I," *IEEE Transactions on Power Systems*, vol. 28, no. 3, Aug. 2013, pp. 2554–2564. DOI: 10.1109/TPWRS.2013.2255317.

[47] M. Farivar, R. Neal, C. Clarke, and S. Low, "Optimal inverter VAR control in distribution systems with high PV penetration," in *2012 IEEE Power and Energy Society General Meeting*, pp. 1–7, Jul. 2012. DOI: 10.1109/PESGM.2012.6345736.

[48] D. M. Fobes, S. Claeys, F. Geth, and C. Coffrin, "Powermodelsdistribution.jl: An open-source framework for exploring distribution power flow formulations," *Electric Power Systems Research*, vol. 189, 2020, p. 106 664. DOI: https://doi.org/10.1016/j.epsr.2020.106664.

[49] K. Forsten, "Green circuits: Distribution efficiency case studies.," EPRI,Palo Alto, CA: 2011. 1023518., Tech. Rep., 2011.

[50] L. Gan and S. H. Low, "Convex relaxations and linear approximation for optimal power flow in multiphase radial networks," in *Power Systems Computation Conference (PSCC), 2014*, IEEE, pp. 1–9, 2014.

[51] Y. Gao and N. Yu, "Deep reinforcement learning in power distribution systems: Overview, challenges, and opportunities," in *2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, IEEE, pp. 1–5, 2021.

[52] P. A. N. Garcia, J. L. R. Pereira, S. Carneiro, V. M. da Costa, and N. Martins, "Three-phase power flow calculations using the current injection method," *IEEE Transactions on Power Systems*, vol. 15, no. 2, May 2000, pp. 508–514. DOI: 10.1109/59.867133.

[53] T. Gonen, *Electric power distribution engineering.* CRC press, 2015.

[54] I. Gorton, J. Yin, B. Akyol, S. Ciraci, T. Critchlow, Y. Liu, T. Gibson, P. Sumit, S. Poorva, and M. Vlachopoulou, "Gridoptics (tm) a novel software framework for integrating power grid data storage, management and analysis," in *2013 46th Hawaii International Conference on System Sciences*, IEEE, pp. 2167–2176, 2013.

[55] B. Green, "Grid Strategy 2011: Conservation Voltage Reduction and Volt VAR Optimization in the Smart Grid," EPRI,Palo Alto, CA: 2011. 1024482., Tech. Rep., 2010.

[56] GridLAB-D. (2017). "GridLAB-D, The Next-Generation Simulation Software," URL: https://www.gridlabd.org/.

[57] GridOPTICS Software System (GOSS), *Pacific Northwest National Laboratory.* URL: https://github.com/GRIDAPPSD/GOSS-GridAPPS-D.

[58] S. S. Guggilam, E. Dall'Anese, Y. C. Chen, S. V. Dhople, and G. B. Giannakis, "Scalable optimization methods for distribution networks with high PV integration," *IEEE Transactions on Smart Grid*, vol. 7, no. 4, 2016, pp. 2061–2070.

[59] T. T. Hashim, A. Mohamed, and H. Shareef, "A review on voltage control methods for active distribution networks," *Electrical review*, 2012.

[60] X. Hu, Z.-W. Liu, G. Wen, X. Yu, and C. Li, "Branch-wise parallel successive algorithm for online voltage regulation in distribution networks," *IEEE Transactions on Smart Grid*, vol. 10, no. 6, 2019, pp. 6678–6689.

[61] Q. Huang, R. Huang, W. Hao, J. Tan, R. Fan, and Z. Huang, "Adaptive power system emergency control using deep reinforcement learning," *IEEE Transactions on Smart Grid*, vol. 11, no. 2, 2019, pp. 1171–1182.

[62] R. Huang, Y. Chen, T. Yin, X. Li, A. Li, J. Tan, W. Yu, Y. Liu, and Q. Huang, "Accelerated deep reinforcement learning based load shedding for emergency voltage control," *arXiv preprint arXiv:2006.12667*, 2020.

[63] M. Huneault and F. Galiana, "A survey of the optimal power flow literature," *IEEE Transactions on Power Systems*, vol. 6, no. 2, 1991, pp. 762–770. DOI: 10.1109/59.76723.

[64] A. Inaolaji, A. Savasci, and S. Paudyal, "Distribution grid optimal power flow in unbalanced multiphase networks with volt-var and volt-watt droop settings of smart inverters," *IEEE Transactions on Industry Applications*, vol. 58, no. 5, 2022, pp. 5832–5843. DOI: 10.1109/TIA.2022.3181110.

[65] R. Jabr, "Radial distribution load flow using conic programming," *IEEE Transactions on Power Systems*, vol. 21, no. 3, 2006, pp. 1458–1459. DOI: 10.1109/TPWRS.2006.879234.

[66] R. R. Jha and A. Dubey, "Exact distribution optimal power flow (d-opf) model using convex iteration technique," in *2019 IEEE Power Energy Society General Meeting (PESGM)*, pp. 1–5, Aug. 2019. DOI: 10.1109/PESGM40551.2019.8974080.

[67] R. R. Jha, A. Inaolaji, B. D. Biswas, A. Suresh, A. Dubey, S. Paudyal, and S. Kamalasadan, "Distribution grid optimal power flow (d-opf): Modeling, analysis, and benchmarking," *IEEE Transactions on Power Systems*, 2022, pp. 1–14. DOI: 10.1109/TPWRS.2022.3204227.

[68] R. R. Jha and A. Dubey, "Network-level optimization for unbalanced power distribution system: Approximation and relaxation," *IEEE Transactions on Power Systems*, vol. 36, no. 5, 2021, pp. 4126–4139. DOI: 10.1109/TPWRS.2021.3066146.

[69] R. R. Jha, A. Dubey, C.-C. Liu, and K. P. Schneider, "Bi-level volt-var optimization to coordinate smart inverters with voltage control devices," *IEEE Transactions on Power Systems*, vol. 34, no. 3, 2019, pp. 1801–1813.

[70] X. Jiang, Y. Zhou, W. Ming, P. Yang, and J. Wu, "An overview of soft open points in electricity distribution networks," *IEEE Transactions on Smart Grid*, vol. 13, no. 3, 2022, pp. 1899–1910. DOI: 10.1109/TSG.2022.3148599.

[71] V. Kekatos, L. Zhang, G. B. Giannakis, and R. Baldick, "Fast localized voltage regulation in single-phase distribution grids," in *2015 IEEE International Conference on Smart Grid Communications (SmartGridComm)*, pp. 725–730, Nov. 2015. DOI: 10.1109/SmartGridComm.2015.7436387.

[72] W. H. Kersting, "Distribution system modeling and analysis," in *Electric Power Generation, Transmission, and Distribution: The Electric Power Engineering Handbook*, CRC press, 2018, pp. 26–1.

[73] V. Khadkikar, "Enhancing electric power quality using upqc: A comprehensive overview," *IEEE Transactions on Power Electronics*, vol. 27, no. 5, 2012, pp. 2284–2297. DOI: 10.1109/TPEL.2011.2172001.

[74] S. Khushalani, J. M. Solanki, and N. N. Schulz, "Optimized restoration of unbalanced distribution systems," *IEEE Transactions on Power Systems*, vol. 22, no. 2, 2007, pp. 624–630.

[75] B. H. Kim and R. Baldick, "Coarse-Grained Distributed Optimal Power Flow," *IEEE Transactions on Power Systems*, vol. 12, no. 2, 1997, pp. 932–939. DOI: 10.1109/59.589777.

[76] B. H. Kim and R. Baldick, "A Comparison of Distributed Optimal Power Flow Algorithms," *IEEE Transactions on Power Systems*, vol. 15, no. 2, 2000, pp. 599–604. DOI: 10.1109/59.867147.

[77] J. Kirk, "Count loops in a graph," MathWorks, 2020. URL: https://www.mathworks.com/matlabcentral/fileexchange/10722-count-loops-in-a-graph.

[78] D. Kovaleski. (2022). "Dominion Energy Virginia taps Generac Grid Services for distributed energy resource management," URL: https://dailyenergyinsider.com/news/36507-dominion-energy-virginia-taps-generac-grid-services-for-distributed-energy-resource-management/ (accessed on 03/03/2023).

[79] G. Krishnamoorthy and A. Dubey, "Reinforcement learning for battery energy storage dispatch augmented with model-based optimizer," *CoRR*, vol. abs/2109.01659, 2021. arXiv: 2109.01659. URL: https://arxiv.org/abs/2109.01659.

[80] G. Krishnamoorthy, A. Dubey, and A. H. Gebremedhin, "An open-source environment for reinforcement learning in power distribution systems," in *2022 IEEE Power & Energy Society General Meeting (PESGM)*, pp. 1–5, 2022. DOI: 10.1109/PESGM48719.2022.9916862.

[81] Y. Kumar, B. Das, and J. Sharma, "Service restoration in distribution system using non-dominated sorting genetic algorithm," *Electric Power Systems Research*, vol. 76, no. 9-10, 2006, pp. 768–777.

[82] H. Lange, B. Chen, M. Berges, and S. Kar, "Learning to solve ac optimal power flow by differentiating through holomorphic embeddings," *arXiv preprint arXiv:2012.09622*, 2020.

[83] J. Lei, Y. Deng, Y. He, and B. Zhang, "Network reconfiguration in unbalanced distribution systems for service restoration and loss reduction," in *Power Engineering Society Winter Meeting, 2000. IEEE*, IEEE, vol. 4, pp. 2345–2350, 2000.

[84] P. Li, C. Zhang, Z. Wu, Y. Xu, M. Hu, and Z. Dong, "Distributed adaptive robust voltage/var control with network partition in active distribution networks," *IEEE Transactions on Smart Grid*, vol. 11, no. 3, 2020, pp. 2245–2256.

[85] Q. Li and V. Vittal, "Non-iterative enhanced SDP relaxations for optimal scheduling of distributed energy storage in distribution systems," *IEEE Transactions on Power Systems*, vol. 32, no. 3, 2017, pp. 1721–1732.

[86] Z. Li, X. Chen, K. Yu, Y. Sun, and H. Liu, "A hybrid particle swarm optimization approach for distribution network reconfiguration problem," in *PES GM-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, IEEE, pp. 1–7, 2008.

[87] C.-C. Liu, S. J. Lee, and S. Venkata, "An expert system operational aid for restoration and loss reduction of distribution systems," *IEEE Transactions on Power Systems*, vol. 3, no. 2, 1988, pp. 619–626.

[88] Y. Liu, J. Bebic, B. Kroposki, J. de Bedout, and W. Ren, "Distribution system voltage performance analysis for high-penetration pv," in *2008 IEEE Energy 2030 Conference*, pp. 1–8, 2008. DOI: 10.1109/ENERGY.2008.4781069.

[89] S. H. Low, "Convex relaxation of optimal power flow Part II: Exactness," *IEEE Transactions on Control of Network Systems*, vol. 1, no. 2, Jun. 2014, pp. 177–189. DOI: 10.1109/TCNS.2014.2323634.

[90] S. Magnússon, P. C. Weeraddana, and C. Fischione, "A distributed approach for the optimal power-flow problem based on admm and sequential convex approximations," *IEEE Transactions on Control of Network Systems*, vol. 2, no. 3, 2015, pp. 238–253.

[91] B. McMillan, P. Guido, O. Leitermann, V. Martinelli, A. Gonzaga, and R. McFetridge, "Application of power electronics lv power regulators in a utility distribution system," in *2015 IEEE Rural Electric Power Conference*, pp. 43–47, 2015. DOI: 10.1109/REPC.2015.15.

[92] R. B. Melton, K. P. Schneider, E. Lightner, T. E. Mcdermott, P. Sharma, Y. Zhang, F. Ding, S. Vadari, R. Podmore, A. Dubey, R. W. Wies, and E. G. Stephan, "Leveraging standards to create an open platform for the development of advanced distribution applications," *IEEE Access*, vol. 6, 2018, pp. 37 361–37 370. DOI: 10.1109/ACCESS.2018.2851186.

[93] B. Millar and D. Jiang, "Smart grid optimization through asynchronous, distributed primal dual iterations," *IEEE Transactions on Smart Grid*, vol. 8, no. 5, 2016, pp. 2324–2331.

[94] K. N. Miu, H.-D. Chiang, and R. J. McNulty, “Multi-tier service restoration through network reconfiguration and capacitor control for large-scale radial distribution networks,” *IEEE Transactions on Power Systems*, vol. 15, no. 3, 2000, pp. 1001–1007.

[95] D. K. Molzahn, F. Dörfler, H. Sandberg, S. H. Low, S. Chakrabarti, R. Baldick, and J. Lavaei, “A survey of distributed optimization and control algorithms for electric power systems,” *IEEE Transactions on Smart Grid*, vol. 8, no. 6, 2017, pp. 2941–2962.

[96] D. K. Molzahn and I. A. Hiskens, “A survey of relaxations and approximations of the power flow equations,” *Foundations and Trends® in Electric Energy Systems*, vol. 4, no. 1-2, 2019, pp. 1–221. DOI: 10.1561/3100000012.

[97] J. Momoh, R. Adapa, and M. El-Hawary, “A review of selected optimal power flow literature to 1993. i. nonlinear and quadratic programming approaches,” *IEEE Transactions on Power Systems*, vol. 14, no. 1, 1999, pp. 96–104. DOI: 10.1109/59.744492.

[98] National Academies of Sciences, Engineering, and Medicine, *Enhancing the Resilience of the Nation’s Electricity System*. National Academies Press, 2017.

[99] N. Nazir and M. Almassalkhi, “Receding-horizon optimization of unbalanced distribution systems with time-scale separation for discrete and continuous control devices,” in *2018 Power Systems Computation Conference (PSCC)*, pp. 1–7, 2018.

[100] Y. Ngo, H. Arant, C. Bilby, and A. Grice, “Investing for the future: How small utilities are finding success with advanced distribution management systems,” *IEEE Power and Energy Magazine*, vol. 18, no. 1, 2020, pp. 34–42.

[101] OpenDSS, *Electric Power Research Institute (EPRI), Simulation Tool-OpenDSS*, 2008.

[102] Pacific Northwest National Laboratory (PNNL), *Gridapps-d documentation–data model*, 2021. URL: https://gridappsd.readthedocs.io/en/master/overview/index.html.

[103] H. V. Padullaparti, Q. Nguyen, and S. Santoso, "Advances in volt-var control approaches in utility distribution systems," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, pp. 1–5, Jul. 2016. DOI: 10.1109/PESGM.2016.7741366.

[104] H. V. Padullaparti, P. Chirapongsananurak, S. Santoso, and J. A. Taylor, "Edge-of-grid voltage control: Device modeling, strategic placement, and application considerations," *IEEE Power and Energy Technology Systems Journal*, vol. 4, no. 4, 2017, pp. 106–114. DOI: 10.1109/JPETS.2017.2750479.

[105] H. V. Padullaparti, S. Jothibasu, S. Santoso, and G. Todeschini, "Increasing feeder pv hosting capacity by regulating secondary circuit voltages," in *2018 IEEE Power & Energy Society General Meeting (PESGM)*, pp. 1–5, 2018. DOI: 10.1109/PESGM.2018.8586615.

[106] H. V. Padullaparti, M. Lwin, and S. Santoso, "Optimal placement of edge-of-grid low-voltage svcs in real-world distribution circuits," in *2017 IEEE Workshop on Power Electronics and Power Quality Applications (PEPQA)*, pp. 1–6, 2017. DOI: 10.1109/PEPQA.2017.7981646.

[107] H. V. Padullaparti, Q. Nguyen, and S. Santoso, "Advances in volt-var control approaches in utility distribution systems," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, pp. 1–5, 2016. DOI: 10.1109/PESGM.2016.7741366.

[108] S. Paudyal, C. A. Cañizares, and K. Bhattacharya, "Optimal Operation of Distribution Feeders in Smart Grids," *IEEE Trans. on Ind. Electron.*, vol. 58, no. 10, Oct. 2011, pp. 4495–4503.

[109] S. Paudyal, C. A. Cañizares, and K. Bhattacharya, "Three-phase distribution opf in smart grids: Optimality versus computational burden," in *2011 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies*, pp. 1–7, Dec. 2011. DOI: 10.1109/ISGTEurope.2011.6162628.

[110] Q. Peng and S. H. Low, "Distributed Algorithm for Optimal Power Flow on a Radial Network," in *53rd IEEE Conference on Decision and Control*, pp. 167–172, 2014. DOI: 10.1109/CDC.2014.7039376.

[111] Q. Peng and S. H. Low, "Distributed Algorithm for Optimal Power Flow on an Unbalanced Radial Network," in *2015 54th IEEE Conference on Decision and Control (CDC)*, pp. 6915–6920, 2015. DOI: 10.1109/CDC.2015.7403309.

[112] Q. Peng and S. H. Low, "Distributed Optimal Power Flow Algorithm for Radial Networks, I: Balanced Single Phase Case," *IEEE Transactions on Smart Grid*, vol. 9, no. 1, 2018, pp. 111–121. DOI: 10.1109/TSG.2016.2546305.

[113] S. Poudel, *GridAPPS-D Restoration Application*, 2019. URL: https://github.com/shpoudel/WSU-Restoration.

[114] S. Poudel, *Network data structure of distribution feeders from OpenDSS*, 2019. URL: https://github.com/shpoudel/D-Net.

[115] S. Poudel, *WSU-Restoration Application Documentation*, 2019. URL: https://wsu-restoration.readthedocs.io/en/latest/.

[116] S. Poudel and A. Dubey, "Critical load restoration using distributed energy resources for resilient power distribution system," *IEEE Transactions on Power Systems*, vol. 34, no. 1, 2019, pp. 52–63. DOI: 10.1109/TPWRS.2018.2860256.

[117] S. Poudel and A. Dubey, "A two-stage service restoration method for electric power distribution systems," *IET Smart Grid*, vol. 4, no. 5, Mar. 2021. DOI: 10.1049/stg2.12021.

[118] S. Poudel, A. Dubey, and A. Bose, "Risk-based probabilistic quantification of power distribution system operational resilience," *IEEE Systems Journal*, vol. 14, no. 3, 2020, pp. 3506–3517. DOI: 10.1109/JSYST.2019.2940939.

[119] S. Poudel, A. Dubey, and K. P. Schneider, "A generalized framework for service restoration in a resilient power distribution system," *IEEE Systems Journal*, vol. 16, no. 1, 2022, pp. 252–263. DOI: 10.1109/JSYST.2020.3011901.

[120] S. Poudel, P. Sharma, A. Dubey, and K. P. Schneider, "Advanced FLISR with intentional islanding operations in an ADMS environment using GridAPPS-D," *IEEE Access*, vol. 8, 2020, pp. 113 766–113 778. DOI: 10.1109/ACCESS.2020.3003325.

[121] G. Qu and N. Li, "Optimal distributed feedback voltage control under limited reactive power," *IEEE Transactions on Power Systems*, vol. 35, no. 1, 2019, pp. 315–331.

[122] H. Ren, R. R. Jha, A. Dubey, and N. N. Schulz, “Extremum-seeking adaptive-droop for model-free and localized volt-var optimization,” *IEEE Transactions on Power Systems*, vol. 37, no. 1, 2022, pp. 179–190. DOI: 10.1109/TPWRS.2021.3093831.

[123] B. A. Robbins, H. Zhu, and A. D. Domínguez-García, “Optimal tap setting of voltage regulation transformers in unbalanced distribution systems,” *IEEE Transactions on Power Systems*, vol. 31, no. 1, 2016, pp. 256–267.

[124] R. Sadnan and A. Dubey, “Real-time distributed control of smart inverters for network-level optimization,” in *2020 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, IEEE, pp. 1–6, 2020.

[125] R. Sadnan and A. Dubey, “Distributed optimization using reduced network equivalents for radial power distribution systems,” *IEEE Transactions on Power Systems*, 2021.

[126] R. Sadnan, S. Poudel, A. Dubey, and K. P. Schneider, “Layered coordination architecture for resilient restoration of power distribution systems,” *IEEE Transactions on Industrial Informatics*, 2022, pp. 1–1. DOI: 10.1109/TII.2022.3177464.

[127] M. D. Sankur, R. Dobbe, E. Stewart, D. S. Callaway, and D. B. Arnold, “A linearized power flow model for optimization in unbalanced distribution systems,” *arXiv preprint arXiv:1606.04492*, 2016.

[128] A. Savasci, A. Inaolaji, and S. Paudyal, “Two-stage volt-var optimization of distribution grids with smart inverters and legacy devices,” *IEEE Transactions on Industry Applications*, vol. 58, no. 5, 2022, pp. 5711–5723. DOI: 10.1109/TIA.2022.3183182.

[129] A. Savasci, A. Inaolaji, S. Paudyal, and S. Kamalasadan, “Efficient distribution grid optimal power flow with discrete control of legacy grid devices,” in *2021 IEEE Power & Energy Society General Meeting (PESGM)*, pp. 1–5, 2021. DOI: 10.1109/PESGM46819.2021.9638228.

[130] K. P. Schneider, Y. Chen, D. Engle, and D. Chassin, “A taxonomy of north american radial distribution feeders,” in *IEEE PES General Meeting, 2009*, IEEE, pp. 1–5, 2009.

[131] K. P. Schneider, B. A. Mather, B. C. Pal, C. W. Ten, G. J. Shirek, H. Zhu, J. C. Fuller, J. L. R. Pereira, L. F. Ochoa, L. R. de Araujo, R. C. Dugan, S. Matthias, S. Paudyal, T. E. McDermott, and W. Kersting, "Analytic considerations and design basis for the ieee distribution test feeders," *IEEE Transactions on Power Systems*, vol. 33, no. 3, May 2018, pp. 3181–3188. DOI: 10.1109/TPWRS.2017.2760011.

[132] K. P. Schneider, J. C. Fuller, F. K. Tuffner, and R. Singh, "Evaluation of conservation voltage reduction (CVR) on a national level," PNNL, Richland, WA (US), Tech. Rep., 2010.

[133] K. Schneider, D. Enge, Y. Chen, S. Thompson, D. Chassin, and R. Pratt, "Modern grid initiative distribution taxonomy," November 2008.

[134] S. R. Shukla, S. Paudyal, and M. R. Almassalkhi, "Efficient distribution system optimal power flow with discrete control of load tap changers," *IEEE Transactions on Power Systems*, vol. 34, no. 4, 2019, pp. 2970–2979.

[135] X. Su, M. A. S. Masoum, and P. J. Wolfs, "Optimal pv inverter reactive power control and real power curtailment to improve performance of unbalanced four-wire lv distribution networks," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 3, Jul. 2014, pp. 967–977. DOI: 10.1109/TSTE.2014.2313862.

[136] X. Sun and J. Qiu, "Two-stage volt/var control in active distribution networks with multi-agent deep reinforcement learning method," *IEEE Transactions on Smart Grid*, 2021.

[137] Y. T. Tan and D. S. Kirschen, "Impact on the power system of a large penetration of photovoltaic generation," in *2007 IEEE Power Engineering Society General Meeting*, pp. 1–8, 2007. DOI: 10.1109/PES.2007.385563.

[138] L. Thurner, A. Scheidler, F. Schäfer, J.-H. Menke, J. Dollichon, F. Meier, S. Meinecke, and M. Braun, "Pandapower—an open-source python tool for convenient modeling, analysis, and optimization of electric power systems," *IEEE Transactions on Power Systems*, vol. 33, no. 6, 2018, pp. 6510–6521. DOI: 10.1109/TPWRS.2018.2829021.

[139] J.-F. Toubeau, B. Bakhshideh Zad, M. Hupez, Z. De Grève, and F. Vallée, "Deep reinforcement learning-based voltage control to deal with model uncertainties in distribution networks," *Energies*, vol. 13, no. 15, 2020, p. 3928.

[140] F. C. Trindade, T. S. Ferreira, M. G. Lopes, and W. Freitas, "Mitigation of fast voltage variations during cloud transients in distribution systems with pv solar farms," *IEEE Transactions on Power Delivery*, vol. 32, no. 2, 2017, pp. 921–932.

[141] K. Turitsyn, P. Sulc, S. Backhaus, and M. Chertkov, "Local control of reactive power by distributed photovoltaic generators," in *Proc. First IEEE International Conference on Smart Grid Communications*, pp. 79–84, 2010.

[142] K. Turitsyn, P. Sulc, S. Backhaus, and M. Chertkov, "Options for control of reactive power by distributed photovoltaic generators," *Proceedings of the IEEE*, vol. 99, no. 6, 2011, pp. 1063–1073. DOI: 10.1109/JPROC.2011.2116750.

[143] UK Open Networks Project, *UK Open Networks 2017-2022*, https://www.energynetworks.org/creating-tomorrows-networks/open-networks/2017-2022, 2022.

[144] B. Wang, Y. Li, W. Ming, and S. Wang, "Deep reinforcement learning method for demand response management of interruptible load," *IEEE Transactions on Smart Grid*, vol. 11, no. 4, 2020, pp. 3146–3155.

[145] S. Wang, J. Duan, D. Shi, C. Xu, H. Li, R. Diao, and Z. Wang, "A data-driven multi-agent autonomous voltage control framework using deep reinforcement learning," *IEEE Transactions on Power Systems*, vol. 35, no. 6, 2020, pp. 4644–4654.

[146] W. Wang and N. Yu, "Chordal conversion based convex iteration algorithm for three-phase optimal power flow problems," *IEEE Transactions on Power Systems*, vol. 33, no. 2, Mar. 2018, pp. 1603–1613. DOI: 10.1109/TPWRS.2017.2735942.

[147] W. Wang, N. Yu, Y. Gao, and J. Shi, "Safe off-policy deep reinforcement learning algorithm for volt-var control in power distribution systems," *IEEE Transactions on Smart Grid*, vol. 11, no. 4, 2019, pp. 3008–3018.

[148] Z. Wang, J. Wang, B. Chen, M. M. Begovic, and Y. He, "Mpc-based voltage/var optimization for distribution circuits with distributed generators and exponential load models," *IEEE Transactions on Smart Grid*, vol. 5, no. 5, 2014, pp. 2412–2420.

[149] Z. Wang, D. S. Kirschen, and B. Zhang, "Accurate semidefinite programming models for optimal power flow in distribution systems," *arXiv preprint arXiv:1711.07853*, 2017.

[150] Z. Wang and J. Wang, "Self-healing resilient distribution systems based on sectionalization into microgrids," *IEEE Transactions on Power Systems*, vol. 30, no. 6, 2015, pp. 3139–3149.

[151] J.-P. Watson, A. F. Castillo, P. U. Lipka, S. U. Oren, and R. F. O'Neill, "A current-voltage successive linear programming approach to solving the ACOPF.," Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), Tech. Rep., 2014.

[152] W. L. Winston, M. Venkataramanan, and J. B. Goldberg, *Introduction to mathematical programming*, vol. 1. Thomson/Brooks/Cole Duxbury; Pacific Grove, CA, 2003.

[153] W. Wu, Z. Tian, and B. Zhang, "An exact linearization method for OLTC of transformer in branch flow model," *IEEE Transactions on Power Systems*, vol. 32, no. 3, 2017, pp. 2475–2476.

[154] Q. Yang, G. Wang, A. Sadeghi, G. B. Giannakis, and J. Sun, "Two-timescale voltage control in distribution grids using deep reinforcement learning," *IEEE Transactions on Smart Grid*, vol. 11, no. 3, 2019, pp. 2313–2323.

[155] Z. Yang, H. Zhong, A. Bose, T. Zheng, Q. Xia, and C. Kang, "A linearized OPF model with reactive power and voltage magnitude: A pathway to improve the mw-only DC OPF," *IEEE Transactions on Power Systems*, vol. 33, no. 2, 2018, pp. 1734–1745.

[156] A. S. Zamzam, N. D. Sidiropoulos, and E. Dall'Anese, "Beyond relaxation and newton–raphson: Solving AC OPF for multi-phase systems with renewables," *IEEE Transactions on Smart Grid*, vol. 9, no. 5, 2018, pp. 3966–3975. DOI: 10.1109/TSG.2016.2645220.

[157] D. Zhang, X. Han, and C. Deng, "Review on the research and practice of deep learning and reinforcement learning in smart grids," *CSEE Journal of Power and Energy Systems*, vol. 4, no. 3, 2018, pp. 362–370.

[158] J. Zhang, Y. Li, Z. Wu, C. Rong, T. Wang, Z. Zhang, and S. Zhou, "Deep-reinforcement-learning-based two-timescale voltage control for distribution systems," *Energies*, vol. 14, no. 12, 2021, p. 3540.

[159] Y. Zhang, X. Wang, J. Wang, and Y. Zhang, "Deep reinforcement learning based volt-var optimization in smart distribution systems," *IEEE Transactions on Smart Grid*, vol. 12, no. 1, 2020, pp. 361–371.

[160] C. Zhao, E. Dall-Anese, and S. Low, "Convex relaxation of OPF in multiphase radial networks with wye and delta connections," National Renewable Energy Lab.(NREL), Golden, CO (United States), Tech. Rep., 2017.

[161] H. Zhu and H. J. Liu, "Fast local voltage control under limited reactive power: Optimality and stability analysis," *IEEE Transactions on Power Systems*, vol. 31, no. 5, Sep. 2016, pp. 3794–3803. DOI: 10.1109/TPWRS.2015.2504419.