



Indian Institute of
Technology Delhi



THE UNIVERSITY
OF QUEENSLAND
AUSTRALIA

**OPTIMAL SCHEDULING IN ACTIVE DISTRIBUTION SYSTEM
UNDER UNCERTAIN CONDITIONS**

B.V. SURYAKIRAN

DOCTOR OF PHILOSOPHY

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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THE UNIVERSITY OF QUEENSLAND

JULY 2024

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UNDER UNCERTAIN CONDITIONS**

by

B.V. SURYAKIRAN

Submitted

in fulfillment of the requirements for the joint degree of

DOCTOR OF PHILOSOPHY

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

&

THE UNIVERSITY OF QUEENSLAND

JULY 2024

Dedicated to
My grandmother, parents & brother

Supervisor Certification

This is to certify that the thesis entitled, "**Optimal Scheduling in Active Distribution System Under Uncertain Conditions**" being submitted by **Mr. B.V. Suryakiran** to the Indian Institute of Technology Delhi and The University of Queensland for the award of degree of Doctor of Philosophy is a record of *bonafide* research work carried out by him. **Mr. B.V. Suryakiran** has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results contained in this thesis are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.

Prof. Ashu Verma	Prof. Sukumar Mishra	Prof. Tapan Kumar Saha
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Abstract

Optimal power flow (OPF) algorithms are essential for secure, economical, and reliable power management. However, the increasing integration of renewable energy (RE) sources and flexible demand, such as electric vehicles (EVs), introduces challenges like intermittent generation, uncertainty, reduced system inertia, and energy storage management. To address these, continuous improvements in power management strategies and communication infrastructure are needed. This thesis proposes optimal power management strategies to enhance smart power distribution systems' efficiency. It focuses on optimal day-ahead scheduling for distribution markets, considering RE sources and DR-enabled loads, including EVs, from both system operator and aggregator perspectives.

Initially, a day-ahead scheduling strategy was proposed for active distribution networks rich in distributed energy resources (DERs) to enhance operational flexibility. This strategy utilizes a DSO-centric day-ahead market model incorporating a multi-period, two-stage OPF model to schedule and price both network and non-network DERs. It robustly addresses uncertainties in day-ahead operations arising from local generation, load consumption, and market prices to mitigate intermittency and forecasting risks. A novel bid price function is introduced for local distributed solar PV generation to maximize its participation in network services. Additionally, a new scheme for managing and pricing reactive power optimizes the scheduling of voltage support devices within the distribution network. The framework is tested on the IEEE-33 bus balanced test system, evaluating operational planning strategies to assess the overall cost-benefits under varying uncertainty levels.

A holistic approach is proposed for optimal EV management, considering interactions between the system operator, EV aggregator, and EV end-users. This aims to minimize EV charging costs and reduce distribution feeder peak loads, potentially deferring network infrastructure costs. The

growing number of EVs can strain feeder peak demand, necessitating sophisticated demand management solutions. Coordinating EV charging flexibility offers promise in mitigating feeder stress. A three-stage EV scheduling strategy optimizes feeder demand coordination and EV fleet allocation. It starts with EV demand estimation by the aggregator, optimized by the DSO, using a novel pseudo price function (CP-LMP) to reduce charging costs and feeder peaks. The third stage involves maximizing EV allocation by the aggregator. A robust optimization framework hedges uncertainties in EV parameters, demonstrating significant peak load reductions and enhancing distribution system resilience and efficiency amid increasing EV adoption.

Further, a time-constrained EV load management strategy, intended for the EV aggregators has been proposed for enhancing the EV accommodation to maximize the utilization of the EV charging infrastructure. The motivation behind the proposed work is to further reduce end consumer prices by optimally allocating multiple EVs in the same charging timeslots to enhance the number of EVs that can be served. The simulation results and observations of the study indicate a significant increase in the EV accommodation which in turn maximizes the profit for the EV aggregators that can be translated to the EV end-users. Lastly, an operational planning strategy based on the three-stage, feedback-based EV scheduling strategy has been formulated for optimal management of EVs. The motivation for the study is to hedge EV aggregators from the risks arising from variable and uncertain EV loads that could effectively help EV aggregators in the planning of the parameter settings for the day-ahead scheduling frameworks.

Abstract in Hindi

संसाधनों के सुरक्षित, किफायती और विश्वसनीय बिजली प्रबंधन को सुनिश्चित करने के लिए इष्टतम बिजली प्रवाह (ओपीएफ) एल्गोरिदम का व्यापक रूप से उपयोग किया जाता है। हालाँकि, उत्पादन मिश्रण में नवीकरणीय ऊर्जा (आरई) स्रोतों में वृद्धि और इलेक्ट्रिक वाहनों (ईवी) सहित लचीली मांग में वृद्धि, बिजली प्रणाली संचालन के लिए कुछ चुनौतियाँ पैदा करती है। इनमें से कुछ चुनौतियों में आंतरायिक उत्पादन स्रोत, उत्पादन और मांग की अनिश्चितता, सिस्टम की कम जड़ता, आरई स्रोतों से बिजली उत्पादन के इष्टतम उपयोग के लिए ऊर्जा भंडारण प्रणालियों का प्रबंधन आदि शामिल हैं। नतीजतन, सुधार के लिए निरंतर प्रयास किए जा रहे हैं। आरई और लचीले संसाधनों के तेजी से प्रसार को सुविधाजनक बनाने के लिए संचार बुनियादी ढांचे में प्रगति के साथ-साथ मौजूदा बिजली प्रबंधन रणनीतियों। इस संदर्भ में, इस थीसिस में प्रस्तुत कार्य स्मार्ट बिजली वितरण प्रणालियों की दक्षता में सुधार के लिए इष्टतम बिजली प्रबंधन रणनीतियों का प्रस्ताव करता है। आमतौर पर, कई देश बिजली व्यापार के लिए उच्च वोल्टेज स्तर पर निरंतर और आवधिक थोक बिजली बाजार तैनात करते हैं, जिसमें बाजार सहभागियों के लिए नीलामी और बोली लगाई जाती है, जिसके बाद इष्टतम बिजली कार्यक्रम निर्धारित करने के लिए इष्टतम परिचालन रणनीतियाँ अपनाई जाती हैं। थोक बाजारों में, वितरण प्रणाली संचालक और बड़े पावर एग्रीगेटर आमतौर पर अपने पोर्टफोलियो में अंतिम उपभोक्ताओं के लिए बिजली खरीदने या बेचने में भाग लेते हैं। हाल के वर्षों में, वितरण स्तर पर आरई स्रोतों, जैसे छत पीवी सिस्टम, मांग प्रतिक्रिया (डीआर) सक्षम लोड इत्यादि के तेजी से प्रवेश की सुविधा के लिए कम वोल्टेज या वितरण प्रणालियों के लिए समान व्यापारिक मॉडल प्रस्तावित और अध्ययन किए गए हैं। प्रेरणा वितरण स्तर पर ऐसे मॉडलों की शुरुआत का उद्देश्य बिजली प्रणालियों के वांछनीय संचालन को सुनिश्चित करते हुए अंतिम-उपभोक्ता कीमतों को नियंत्रित करना है। थीसिस में किए गए कार्य का उद्देश्य सिस्टम ऑपरेटर और एग्रीगेटर दृष्टिकोण से ईवी सहित आरई स्रोतों और डीआर-सक्षम लोड के इष्टतम प्रबंधन के लिए वितरण बाजारों के लिए इष्टतम दिन-आगे शेड्यूलिंग रणनीतियाँ प्रदान करना है। प्रारंभ में, विभिन्न डीईआर के परिचालन लचीलेपन का लाभ उठाने के लिए डीईआर-समृद्ध सक्रिय वितरण नेटवर्क के लिए एक दिन पहले की शेड्यूलिंग रणनीति प्रस्तावित की गई है। प्रभावी नेटवर्क प्रबंधन के लिए, प्रस्तावित शेड्यूलिंग रणनीति को डीएसओ-केंद्रित डे-अहेड मार्केट मॉडल के आधार पर साकार किया गया है, जिसमें नेटवर्क और गैर-नेटवर्क डीईआर के लिए शेड्यूलिंग और मूल्य निर्धारण निर्धारित करने के लिए एक बहु-अवधि और दो-चरण ओपीएफ मॉडल शामिल है। स्थानीय उत्पादन, लोड खपत और बाजार की कीमतों से उत्पन्न होने वाले दिन-प्रतिदिन

के संचालन में अनिश्चितताओं को आंतरायिकता से बचाव और अनिश्चितताओं की भविष्यवाणी के लिए दृढ़ता से विचार किया जाता है। नेटवर्क सेवा में भागीदारी को अधिकतम करने के उद्देश्य से स्थानीय वितरित सौर पीवी उत्पादन के लिए एक नया बोली मूल्य फ़ंक्शन प्रस्तावित है। वितरण नेटवर्क के भीतर वोल्टेज समर्थन उपकरणों के इष्टतम शेड्यूलिंग के लिए एक नई प्रतिक्रियाशील बिजली प्रबंधन और मूल्य निर्धारण योजना भी प्रस्तुत की गई है। प्रस्तावित रूपरेखा आई ट्रिपल ई-33 बस संतुलित परीक्षण प्रणाली पर लागू की गई है और विभिन्न अनिश्चितता स्तरों पर प्रणाली के समग्र लागत-लाभ के लिए परिचालन योजना रणनीति का विश्लेषण किया गया है। इसके अलावा, ईवी के इष्टतम प्रबंधन के लिए सिस्टम ऑपरेटर और ईवी एग्रीगेटर, और ईवी एग्रीगेटर और ईवी एंड-यूजर्स के बीच बातचीत पर विचार करते हुए एक समग्र दृष्टिकोण प्रस्तावित है। प्रस्तावित कार्य का उद्देश्य वितरण फीडरों के पीक लोड को कम करते हुए ईवी चार्जिंग लागत को कम करना है जो नेटवर्क बुनियादी ढांचे के स्थगन द्वारा चार्जिंग लागत को और कम कर सकता है। ईवी की बढ़ती वृद्धि से वितरण प्रणाली फीडरों पर चरम मांग में वृद्धि हो सकती है, जिसके लिए जटिल और अक्सर महंगे मांग प्रबंधन समाधान की आवश्यकता होती है। ईवी चार्जिंग की मांग लचीलेपन का लाभ उठाने, जब उचित रूप से समन्वित किया जाता है, तो फीडर मांग तनाव को कम करने का वादा किया जाता है। एक तीन चरण वाली ईवी शेड्यूलिंग रणनीति प्रस्तावित है जो ईवी बेड़े को कुशलतापूर्वक आवंटित करते हुए वितरण फीडर मांग को बेहतर ढंग से समन्वयित करती है। पहले चरण में ईवी एग्रीगेटर द्वारा ईवी मांग का अनुमान लगाया जाता है, जिसे ईवी के चार्जिंग लचीलेपन का लाभ उठाते हुए, दूसरे चरण में डीएसओ द्वारा और अधिक अनुकूलित किया जाता है। एक नवीन छद्म मूल्य फ़ंक्शन जिसे "महत्वपूर्ण शिखर में स्थानीय सीमांत कीमतें शामिल हैं" (सीपी-एलएमपी) कहा जाता है, को उद्देश्य फ़ंक्शन के रूप में प्रस्तावित किया गया है जो अंतिम-उपयोग चार्जिंग लागत और फीडर पीक मांग को कम करता है। तीसरे चरण में ईवी एग्रीगेटर द्वारा ईवी आवंटन को अधिकतम करना शामिल है। इसके अलावा, ईवी मापदंडों और उनके वितरण में अनिश्चितताओं से बचाव के लिए एक मजबूत अनुकूलन-आधारित परिचालन योजना ढांचा प्रस्तावित है। प्रस्तावित पद्धति की प्रभावकारिता को मान्य करने के लिए व्यापक विश्लेषण प्रस्तुत किए गए हैं। ईवी प्रवेश, अनुमेय लोड शिफ्टिंग और चार्जिंग स्टेशन क्षमता जैसे कारकों के आधार पर, हमारा दृष्टिकोण पीक लोड में उल्लेखनीय कमी दर्शाता है, जो तेजी से ईवी प्रसार के लिए वितरण प्रणाली के लचीलेपन और दक्षता को बढ़ाने में प्रस्तावित रणनीति के संभावित लाभों को रेखांकित करता है। इसके अलावा, ईवी चार्जिंग बुनियादी ढांचे के उपयोग को अधिकतम करने के लिए ईवी आवास को बढ़ाने के लिए ईवी एग्रीगेटर्स के लिए एक समय-बाधित ईवी लोड प्रबंधन रणनीति प्रस्तावित की गई है। प्रस्तावित कार्य के पीछे प्रेरणा एक ही चार्जिंग टाइम-स्लॉट में कई ईवी आवंटित करके अंतिम उपभोक्ता कीमतों को और कम करना है ताकि परोसी जा सकने वाली ईवी की संख्या बढ़ाई जा सके। अध्ययन के सिमुलेशन परिणाम और अवलोकन ईवी आवास में उल्लेखनीय वृद्धि का संकेत देते हैं जो बदले में ईवी एग्रीगेटर्स के लिए लाभ को अधिकतम करता है जिसे ईवी अंतिम उपयोगकर्ताओं के लिए अनुवादित किया जा सकता है। अंत में, ईवी के इष्टतम प्रबंधन के लिए तीन-चरण, फीडबैक-आधारित ईवी शेड्यूलिंग रणनीति पर आधारित एक परिचालन योजना रणनीति तैयार की गई है। अध्ययन के लिए प्रेरणा ईवी एग्रीगेटर्स को परिवर्तनीय और अनिश्चित ईवी लोड से उत्पन्न होने वाले जोखिमों से बचाना है जो ईवी एग्रीगेटर्स को दिन-आगे शेड्यूलिंग ढांचे के लिए पैरामीटर सेटिंग्स की योजना बनाने में प्रभावी ढंग से मदद कर सकता है। प्रस्तावित

रूपरेखा का अनुकरण किया गया है और परिणाम प्रस्तुत किए गए हैं।

Declaration by Author

This thesis is composed of my original work and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution of others to jointly authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

I acknowledge that an electronic copy of my thesis must be lodged with the University Library and, subject to the policy and procedures of The University of Queensland, the thesis be made available for research and study in accordance with the Copyright Act 1968 unless a period of embargo has been approved by the Dean of the Graduate School.

I acknowledge that the copyright of all material contained in my thesis resides with the copyright holder(s) of that material. Where appropriate I have obtained copyright permission from the copyright holder to reproduce material in this thesis and have sought permission from co-authors for any jointly authored works included in the thesis.

Publications included in this thesis

1. **Suryakiran, B. V.**, Nizami, S., Verma, A., Saha, T. K., & Mishra, S. (2023). A DSO-based day-ahead market mechanism for optimal operational planning of active distribution network. *Energy*, 282, 128902.
2. **Suryakiran, B. V.**, Verma, A., Nizami, S., & Mishra, S. (2022, December). A Bi-level Electric Vehicle Scheduling Strategy in Parking Lots for Peak Load Management. In 2022 22nd National Power Systems Conference (NPSC) (pp. 785-790). IEEE.
3. **Suryakiran, B. V.**, Nizami, S., Mishra, S., & Verma, A. (2022, November). An Optimal Continuous-time Constrained EV Scheduling Strategy for Parking Lots. In 2022 IEEE PES 14th Asia-Pacific Power and Energy Engineering Conference (APPEEC) (pp. 1-6). IEEE.

Submitted manuscripts included in this thesis

1. **Suryakiran, B. V.**, Nizami, S., Verma, A., Saha, T. K., & Mishra, S. A Three-stage Feedback-based Electric Vehicle Scheduling Framework for Peak Load Reduction of Distribution System Feeder Demand. *Journal of Cleaner Production* (under revision).

Other Publications during Candidature

1. Singh, V. K., **Suryakiran, B. V.**, Verma, A., & Bhatti, T. S. (2021). Modelling of a renewable energy-based AC interconnected rural microgrid system for the provision of uninterrupted power supply. *IET Energy Systems Integration*, 3(2), 172-183.

Contribution by Others to the Thesis

All chapters

Editorial suggestions were provided by the supervisory team of the candidate, Prof. Tapan K. Saha (UQ), Prof. Sukumar Mishra (IIT Delhi), Prof. Ashu Verma (IIT Delhi), and Ph.D. committee comprising Prof. Nilanjan Senroy (IIT Delhi), Dr. Wayes Tushar, and Prof. Sumit Kumar Chatopadhyay (UQ).

Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis.

Research involving human or animal subjects

No animal or human subjects were involved in this research.

(to be updated according to the project)

Acknowledgements

This thesis is a compilation of the work I have carried out during my Ph.D. at Indian Institute of Technology Delhi, India (IITD) and The University of Queensland, Australia (UQ). I would like to express my deepest gratitude to my supervisors, **Prof. Ashu Verma**, **Prof. Tapan Kumar Saha**, and **Prof. Sukumar Mishra** for making me a part of their research teams and for their unconditional support throughout my Ph.D. Their experience, knowledge, and research aptitudes have been key factors for fueling my motivation for research. Their patience, constant efforts, and dedication have played a key role in shaping my professional and personal life.

I would also like to thank my ASMC members, Prof. Nilanjan Senroy, Dr. Wayes Tushar, and Prof. Sumit Kumar Chattopadhyay for their valuable feedback on my work. Their constructive comments and invaluable advice have resulted in the enhancement of the presented work. I am also grateful to Prof. Kiran Seth and Prof. T.C. Kandpal for their teachings in the coursework carried out during my candidature, which gratefully helped me in developing concepts presented in the thesis. I sincerely thank Dr. Sohrab Nizami for all the insights on optimization in electricity trading approaches and paper writing skills, which helped me a lot throughout my thesis. I take pleasure in expressing my heartfelt gratitude to the UQIDAR team in IITD and UQ for providing me an opportunity to work in two premier institutions and making my journey hassle-free and joyous.

Further, I extend immense pleasure and joy to my colleagues and friends, Mr. Arnab Bhattacharjee, Dr. Abdullah Bareen, Dr. Imon Chakraborty, Ms. Sonam Mittal, Dr. Bakul Kandpal, Mr. Bevin K.C., Dr. Ram Krishan, Ms. Sapna Verma, Dr. Simran Agarwal, Dr. Sumedha Sharma, Dr. Parikshit Pareek, Dr. Himanshu Grover, Mr. Manish Kumar Yadav, Dr. Neha Tak, Mr. Nikhilesh Wanjari, Mr. Zhixuan Li, Mr. Gaurav Prit, Mr. Utkarsh Kumar, Ms. Anyuti Tiwary, with whom I shared my journey throughout my Ph.D.

Finally, I would like to thank my family, late Ms. Lakshmi Narasamma, Mr. B.V.S. Subrahmanyam, Ms. Aruna Kumari, Mr. B.V. Surya Vardhan for always being there and for their unconditional love, and support at each milestone of my life.

Financial support

This research was supported by an Indian Institute of Technology Delhi Research Scholarship, a Research grant from the UQ-IITD Academy of Research (UQIDAR), and a project funded by the Department of Science and Technology (DST) titled, "Demonstration of Grid Supportive EV Charger and Charging Infrastructure at LT Level (D-EVCI)" with Project code: DST/CERI/MI/SG/2017/080.

Keywords

optimal power flow, active distribution systems, distributed energy resources, electric vehicles, demand response, locational marginal prices, critical peak pricing, marginal pricing, solar PV generation, peak load management.

Australian and New Zealand standard research classifications (ANZSRC)

ANZSRC code: 090607, Power and Energy Systems Engineering (excl. Renewable Power), 60%
ANZSRC code: 090608, Renewable Power and Energy Systems Engineering (excl. Solar Cells), 40%

Fields of research classification

FoR code: 0906, Electrical and Electronic Engineering, 100%

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Abbreviations

ADMM	Alternating Direction of Multipliers Method
ADN	Active Distribution Network
APP	Active Power Pricing
BEMS	Building Energy Management System
BESS	Battery Energy Storage Systems
CM	Congestion Management
CP-LMP	Critical Peak included Locational Marginal Pricing
CPP	Critical Peak Pricing
CUF	Capacity Utilization Factor
DERs	Distributed Energy Resources
DLMPs	Distribution Locational Marginal Prices
DRAs	Demand Response Aggregators
DRL	Deep Reinforcement Learning
DSO	Distribution System Operator
ED	Economic Dispatch
EVCS	Electric Vehicle Charging Station
EVs	Electric Vehicles
GES	Generalized Energy Sources
GES	Generalized Energy Sources
HS	Hydrogen Storage
IBRs	Inverter Based Resources
LCOE	Levelized Cost of Electricity
LMPs	Locational Marginal Prices
MG	Microgrid
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MO	Market Operator

ND	Normal Distribution
OC	Operating Cost
OPF	Optimal Power Flow
PM	Profit Maximization
PTR	Peak time Rebate
RO	Robust Optimization
RTP	Real Time Pricing
SD	Storage Devices
SOCP	Second Order Conic Programming
SP	Stochastic Programming
ST	Storage Tanks
SVCs	Static VAR Compensators
TES	Thermal Energy Sources
ToU	Time of Use
UC	Unit Commitment
VR	Voltage Regulation