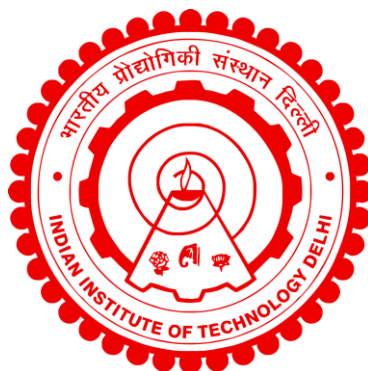


TIME-COORDINATED DISTRIBUTED CONTROL STRATEGY FOR A LOW VOLTAGE ACTIVE DISTRIBUTION NETWORK

MANAS RANJAN MISHRA



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JUNE 2025**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2025

TIME-COORDINATED DISTRIBUTED CONTROL STRATEGY FOR A LOW VOLTAGE ACTIVE DISTRIBUTION NETWORK

by

MANAS RANJAN MISHRA

DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

in fulfillment of requirements of degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE, 2025

न गुरुर अधिकं तत्त्वं न गुरुर अधिक तपः ।
तत्त्व ज्ञानात् परं नास्ति तस्मै श्री गुरवे नमः ॥

----- श्री गुरु स्तोत्रम्

No theory is more than the Master, No spiritual Work
is more than the Master, There is nothing beyond deep
knowledge, but there is Master whom we pray.

----- Shri Guru Stotram

CERTIFICATE

This is to certify that the thesis entitled '**Time-Coodinated Distributed Control Strategy For A Low Voltage Active Distribution Network**', being submitted by **Mr. Manas Ranjan Mishra** to **Indian Institute of Technology, Delhi** is a record of bonafide research work carried out under my supervision and I consider it worthy for consideration of the award of the degree **Doctor of Philosophy** in Electrical Engineering. The results obtained here have not been submitted to any other University or Institute for the award of any degree or diploma.

Prof. Sukumar Mishra

Department of Electrical Engineering

Indian Institute of Technology Delhi

New Delhi - 110016, India.

Date:

Acknowledgments

To my Guide: I am deeply grateful to my mentor, Prof. Sukumar Mishra for his unwavering support, guidance, and encouragement throughout my research journey. His expertise, passion for the subject, and ability to simplify complex concepts have enriched my understanding immensely. The freedom he afforded me in my research empowered me to think deeply, independently, and broadly, covering ideas across domains. I am very grateful to Dr. Mishra for instilling in me the importance of ethical values, which are indispensable not only for academic pursuits but also for personal growth and spiritual fulfillment. Understanding and upholding ethical principles enhances the quality of knowledge gained and contributes significantly to leading a purposeful and meaningful life. By integrating these values into my academic journey, I strive to excel professionally and evolve spiritually, enriching my life profoundly.

To my research committee members and teachers during my coursework: I sincerely thank my doctoral research committee members, Prof. Nilanjan Senroy, Dr. B.K Panigrahi, and Dr. A. Verma, for their invaluable guidance and feedback, shaping my research direction. Gratitude to esteemed teachers like Prof. A.R Abhyankar, Prof. G. Bhuvaneshwari, Dr. Subham Sahoo, Dr. Priyatosh Mahish, and Dr. Deepak Pulugram Reddy for enriching my Ph.D journey with valuable suggestions and motivation.

To all my past teachers: I extend my heartfelt appreciation to my former educators from school, college, and coaching institutes, whose guidance and mentorship equipped me to pursue this esteemed degree.

To my financial Stakeholders: I also thank the Ministry of Human Resource Development (MHRD), Government of India, for providing financial support through a scholarship to complete the Doctoral program at IIT Delhi.

To my teachers of the social circle: I am naturally extroverted and, hence, actively participate in campus activities. I sincerely thank Prof. Rangan Banerjee, Director of IIT Delhi, for fostering a supportive environment. I am grateful to Shivalik Hostel residents (especially to my juniors and batch mates), including wardens and staff, for nurturing my personal growth. I especially appreci-

ate my labmates from IIT Delhi for their significant contributions to my professional development. I also want to thank my friends from school and college for caring my personal space during the tough times.

To my family members, my friends, and my extended family: I am deeply thankful to my father, Late. Dilip Kumar Mishra; mother, Mrs. Sandhya Mishra; spouse, Mrs Rashmi Mishra, and my extensive family for their invaluable upbringing, sacrifices, and unwavering support, without which my education wouldn't have been possible. I would also like to express sincere gratitude towards my friend Mr. Pankaj Kumar Behera for his unwavering support in the last phase of my Ph.D. career.

— Manas Ranjan Mishra

Abstract

Gradual increasing installation of solar photovoltaic inverters (SPVIs) at the low voltage (LV) network causes over-voltage issues at the SPVI-connected point-of-common-couplings (PCCs) during high irradiance period. The over-voltage issue at the point-of-common-couplings (PCCs) occur due to the inherent radial nature of the distribution network, and it further degrades the Voltage regulation (VR) of the Distribution Transformer (DT). To mitigate the over-voltage in the network, IEEE 1547 recommends the constant QV-droop and PV-droop characteristics in the SPVIs. Due to the high R/X ratio of the lines, active power curtailment (APC) occurs at the SPVIs due to the PV droop. Further, unplanned and dramatically increasing trends in the single-phase converter (SPC) deployment significantly impacts on phase voltage unbalance factor (PVUF) and voltage regulation (VR) of the LV-ADS. High PVUF at the buses may lead to the tripping of SPVIs and poor voltage regulation at the DT.

This thesis focuses on developing novel control strategies for SPVIs and SPCs. A new control philosophy has been formulated in the thesis to minimize the APC issue among the SPVIs. Further, in this thesis, a novel algorithm is formulated to mitigate the over-voltage issue in SPC and SPVI-dominated LV-ADS. To address the above-mentioned issues, an irradiance driven adaptive PQV (IAPQV) droop mechanism is formulated to resolve using the distributed control approach. The IAPQV proposes irradiance driven QV-Droop and PV-Droop to improve voltage regulation in the ADS. In the latter part of the thesis, a time-coordinated leader-follower feedback-based algorithm (CLFFA) is formulated to operate the SPVIs and SPCs. CLFFA is orchestrated in a time-graded approach to reduce the PVUF and improve the VR in the LV-ADS. Both the formulations, IAPQV and CLFFA use a smart and novel cluster selection algorithm (CSA). The basic aim of CSA formulation is to optimally choose a portion of the network that requires attention a priori in terms of PVUF or VR.

Since the IAPQV and CLFFA control methodology makes use of the communication links between SPVIs and SPCs, the resiliency of the links becomes extremely important from both the perspective of utility and prosumer. Hence, to operate these power infrastructures in an efficient

and reliable manner, cooperative/distributed control is incorporated as a control solution. The communication medium is an inherent infrastructure to exhibit cooperative control in microgrids. The measurement states are communicated using the medium. Thereby, the states communicated come under the realm of the attacker. Voltage of the converters in grid-connected/islanded microgrids is one such state that may be vulnerable to cyber attack. Hence, the last part of the thesis details an event-driven resilient control strategy to detect and mitigate such attacks.

Key Words: Single-phase converter, three-phase converter, droop, adaptive, voltage regulation, voltage unbalance.

सारांश

निम्न वोल्टेज (LV) नेटवर्क में सौर फोटोवोल्टिक इनवर्टर्स (SPVIs) की लगातार बढ़ती स्थापना, उच्च विकिरण अवधि के दौरान SPVI से जुड़े बिंदु-सामान्य-संयोजन (PCCs) पर ओवर-वोल्टेज समस्या उत्पन्न करती है। वितरण नेटवर्क की अंतर्निहित रेडियल प्रकृति के कारण PCCs पर ओवर-वोल्टेज समस्या होती है, जो वितरण ट्रांसफार्मर (DT) के वोल्टेज विनियमन (VR) को और भी खराब करती है। नेटवर्क में ओवर-वोल्टेज को कम करने के लिए, IEEE 1547 SPVIs में स्थिर QV-ड्रूप और PV-ड्रूप विशेषताओं की अनुशंसा करता है। उच्च R/X अनुपात के कारण PV ड्रूप की वजह से SPVIs पर सक्रिय पावर कटौती (APC) होती है। इसके अलावा, सिंगल-फेज़ कन्वर्टर (SPC) की अनियोजित और अत्यधिक बढ़ती प्रवृत्ति चरण वोल्टेज असंतुलन कारक (PVUF) और LV-ADS के वोल्टेज विनियमन (VR) पर महत्वपूर्ण प्रभाव डालती है। बसों पर उच्च PVUF SPVIs के ट्रिपिंग और DT पर खराब वोल्टेज विनियमन का कारण बन सकती है।

यह शोध SPVIs और SPCs के लिए नवीन नियंत्रण रणनीतियों के विकास पर केंद्रित है। इस शोध में SPVIs के बीच APC समस्या को कम करने के लिए एक नया नियंत्रण दृष्टिकोण तैयार किया गया है। इसके अतिरिक्त, SPC और SPVI-प्रधान LV-ADS में ओवर-वोल्टेज समस्या को कम करने के लिए एक नया एल्गोरिथ्म तैयार किया गया है। उपरोक्त मुद्दों को हल करने के लिए, एक विकिरण-निर्देशित अनुकूली PQV (IAPQV) ड्रूप तंत्र तैयार किया गया है, जो वितरित नियंत्रण दृष्टिकोण का उपयोग करता है। IAPQV वोल्टेज विनियमन में सुधार के लिए ADS में विकिरण-निर्देशित QV-ड्रूप और PV-ड्रूप का प्रस्ताव करता है। शोध के बाद के भाग में, SPVIs और SPCs के संचालन के लिए एक समन्वित नेता-अनुयायी प्रतिक्रिया-आधारित एल्गोरिथ्म (CLFFA) तैयार किया गया है। CLFFA को समय-क्रमबद्ध तरीके से PVUF को कम करने और LV-ADS में VR में सुधार करने के लिए व्यवस्थित किया गया है। दोनों IAPQV और CLFFA स्मार्ट और नवीन क्लस्टर चयन एल्गोरिथ्म (CSA) का उपयोग करते हैं। CSA का मुख्य उद्देश्य PVUF या VR के संदर्भ में नेटवर्क के उस हिस्से को चुनना है, जिसमें पहले से ध्यान देने की आवश्यकता है।

चूंकि IAPQV और CLFFA नियंत्रण पद्धतियां SPVIs और SPCs के बीच संचार लिंक का उपयोग करती हैं, इसलिए इन लिंक की लचीलापन उपयोगिता और उपभोक्ता दोनों के दृष्टिकोण से अत्यधिक महत्वपूर्ण हो जाती है। इसलिए, इन ऊर्जा संरचनाओं को कुशल और विश्वसनीय तरीके से संचालित करने के लिए सहकारी/वितरित नियंत्रण को एक समाधान के रूप में शामिल किया गया है। माइक्रोग्रिड में सहकारी नियंत्रण प्रदर्शित करने के लिए संचार माध्यम एक अंतर्निहित संरचना है। माप राज्यों को इस माध्यम का उपयोग करके संचारित किया जाता है, जिससे वे हमलावरों के लिए संवेदनशील बन जाते हैं। माइक्रोग्रिड में कन्वर्टर्स के वोल्टेज ऐसे राज्य हैं जो साइबर हमले के प्रति कमजोर हो सकते हैं। इसलिए, शोध के अंतिम भाग में, इस प्रकार के हमलों का पता लगाने और उन्हें कम करने के लिए एक इवेंट-आधारित लचीली नियंत्रण रणनीति का विवरण दिया गया है।

मुख्य शब्द: सिंगल-फेज़ कन्वर्टर, थ्री-फेज़ कन्वर्टर, ड्रूप, अनुकूली, वोल्टेज विनियमन, वोल्टेज असंतुलन।

Contents

Certificate	i
Acknowledgments	iii
Abstract	vii
Contents	x
List of Figures	xiv
List of Tables	xix
Nomenclature	xxi
1 Introduction to Coordinated and Distributed Control strategy in Low Voltage Active Distribution System (LV-ADS)	1
1.1 Introduction	1
1.2 General Overview of System Level	7
1.2.1 Major Research Gaps in the Existing Literature	8
1.3 Methodology and Datasets Used	11
1.3.1 Research Methodology	11
1.3.2 Datasets Used	15
1.4 Objective and Chapter-Wise Contributions	16

1.4.1	Objective-I: An Irradiance Driven Adaptive PQV Droop for Voltage Regulation in Active Distribution System.	16
1.4.2	Objective 2: Time Coordinated Control Strategy to Improve Voltage Balance and Regulation of Low Voltage PV Rich Networks.	17
1.4.3	Objective 3: Resilient Voltage Restoration Scheme for AC grid connected/islanded Microgrids Under Cyber Attack.	18
1.5	Thesis Outline and Linkage	19
2	An Irradiance Driven Adaptive PQV Droop for Voltage Regulation in Active Distribution System	21
2.1	Introduction	21
2.1.1	Problem Formulation	22
2.1.2	Contribution of this Work	24
2.2	Proposed Methodology	24
2.2.1	Cluster Formation in Radial LV-ADS and Cluster Coordination	26
2.2.2	Proposed TBP Algorithm for i^{th} Cluster	28
2.2.3	Proposed Irradiance Driven PV-Droop Control for $SPVI_j^i$	31
2.2.4	Proposed Irradiance Driven QV-Droop Control for $SPVI_j^i$	32
2.3	Simulation Result	33
2.3.1	Case 1: PV Rich Radial LV-ADS	33
2.3.2	Case 2: Validation of the Proposed control Approach in IEEE 33 Radial Bus System	43
2.4	Discussion	49
3	Time Coordinated Control Strategy to Improve Voltage Balance and Regulation of Low Voltage PV Rich Networks	51
3.1	Introduction	51
3.1.1	Problem Formulation	52

3.1.2	Novelty of The Proposed Approach	53
3.2	Cluster Formation in the LV-ADS	53
3.3	Proposed Methodology	54
3.3.1	Proposed CSA	55
3.3.2	Proposed CLFFA at k^{th} Cluster	59
3.4	Performance Evaluation	67
3.4.1	Solar Irradiance Intermittency Effect on Voltage Profile of the Test Bench .	68
3.4.2	Impact of RPS on APC of the TPCs	71
3.4.3	Impact of Communication Delays and Data Loss on the Proposed Method .	72
3.5	Discussion	75
4	Resilient Voltage Restoration Scheme for AC grid connected/Microgrids Under Cyber	
	Attack	77
4.1	Introduction	77
4.2	Problem Formulation	78
4.3	Ideas and Contribution	78
4.4	Proposed Event Driven Cyber Resilient Consensus-based Cooperative Control . . .	80
4.5	Results	84
4.6	Discussion	88
5	Conclusion and Future works	90
5.1	Conclusion	90
5.1.1	Reflective Insights Based on the Research Outcomes	92
5.2	Future Work	93
	List of Publications	100
	Biodata	102

List of Figures

2.1	Grid voltage support through reactive and active power control of SPVI units per IEEE 1547-2020 (a) QV-droop (volt-var) (b) PV-droop (volt-watt).	23
2.2	Single line diagram of an ADS.	23
2.3	Variations in voltage at the PCCs of an SPVI based ADS.	24
2.4	Schematic layout of proposed IAPQV droop control for an SPVI-connected LV-ADS.	25
2.5	Flowchart of the proposed TBP algorithm for i^{th} cluster at DA- i	26
2.6	Control architecture of proposed IAPQV droop control of $SPVI_j^i$	30
2.7	Proposed PV droop curve of $SPVI_j^i$	30
2.8	Proposed QV droop curve of $SPVI_j^i$	31
2.9	Single line diagram of a radial LV-ADS.	35
2.10	Voltage variations at the LV-terminal of DT in radial LV-ADS for the irradiance change scenario.	36
2.11	Reactive power variations of DT in radial LV-ADS for the irradiance change scenario.	36
2.12	Reactive power variations of the SPVIs with IEEE 1547 in radial LV-ADS for the irradiance change scenario.	37
2.13	Reactive power variations of the SPVIs with IAPQV droop control in radial LV-ADS for the irradiance change scenario.	37
2.14	Active Power injection to the grid from SPVIs with IEEE 1547 droop control in radial LV-ADS for the irradiance change scenario.	38

2.15	Active Power injection to the grid from SPVIs with IAPQV droop control in radial LV-ADS for the irradiance change scenario.	38
2.16	Voltage variations of the SPVI connected PCCs with IEEE 1547 droop control in radial LV-ADS for the irradiance change scenario.	39
2.17	Voltage variations of the SPVI connected PCCs with IAPQV droop control in radial LV-ADS for the irradiance change.	39
2.18	Fast cloud movement along the clusters in radial LV-ADS.	40
2.19	Box plot of voltage at the SPVI connected PCCs for fast cloud movement in radial LV-ADS with IAPQV droop control.	40
2.20	Multiple load change scenario of the radial LV-ADS.	41
2.21	Voltage variations at the LV-terminal of DT in radial LV-ADS for the load change scenario.	41
2.22	Voltage variations of the SPVI connected PCCs in Cluster-1 with IEEE-1547-2020 droop control in radial LV-ADS for the load change scenario.	42
2.23	Voltage variations of the SPVI connected PCCs in Cluster-1 with proposed IAPQV droop control in radial LV-ADS for the load change scenario.	42
2.24	Voltage variations of the SPVI connected PCCs in Cluster-3 with IEEE-1547-2020 droop control in radial LV-ADS for the load change scenario.	43
2.25	Voltage variations of the SPVI connected PCCs in Cluster-3 with proposed IAPQV droop control in radial LV-ADS for the load change.	43
2.26	APC in SPVIs for the load change scenario in radial LV-ADS with IEEE 1547 droop control and proposed IAPQV droop control.	44
2.27	Voltage variations at the LV-terminal of DT for the load change scenario, considering different delay distributions as in Table I.	44
2.28	Single line diagram of IEEE 33 bus LV-ADS divided into multiple clusters with SPVIs.	45
2.29	PV profile data from NREL for a sunny day and a cloudy day.	45

2.30	Box plot of the voltages of DT (LV-terminal), $SPVI_{10}^2$ (Bus no-33), and $SPVI_{15}^3$ (Bus no-18) in IEEE 33 bus LV-ADS with IEEE 1547 droop control.	46
2.31	Box plot of the voltages of DT (LV-terminal), $SPVI_{10}^2$ (Bus no-33), and $SPVI_{15}^3$ (Bus no-18) in IEEE 33 bus LV-ADS with IAPQV droop control.	46
2.32	APC ($\Delta P_{curtail}$) and reactive power support (Q_{ref}) by SPVIs in IEEE 33 bus LV-ADS for the sunny day with IEEE 1547 droop control.	47
2.33	APC ($\Delta P_{curtail}$) and reactive power support (Q_{ref}) by SPVIs in IEEE 33 bus LV-ADS for the sunny day with IAPQV droop control.	47
2.34	Voltage at DT (LV-terminal), $SPVI_{10}$ and $SPVI_{15}$ for the cloudy day in IEEE 33 bus LV-ADS with the proposed IAPQV droop control.	48
2.35	Voltage at the PCC point of $SPVI_{15}$ in IEEE 33 bus LV-ADS under different data loss conditions.	49
3.1	System diagram and communication layout of the intra-cluster (blue dotted line), and inter-cluster and cluster (brown dotted line) in a n -bus radial LV-ADS.	52
3.2	Proposed CLFFA to generate at z^{th} instant (a.) $Q_{j,a}^{i,ref}$ for $SPC_{j,a}^i$ (b.) $P_{i,ref}^k$ and $Q_{i,ref}^k$ for TPC_i^k	62
3.3	Proposed CLFFA-based PVUF control architecture for $SPC_{j,a}^i$	63
3.4	Proposed CLFFA-based VR control architecture for the TPC_i^k	64
3.5	Droop curves of TPC_i^k a. AQV b. APV	65
3.6	Test bench of European LV-ADS	69
3.7	Solar-irradiance profile of the cloudy day on June 17 th 2023.	70
3.8	PVUF at bus-34 and bus-35 with IEEE-1547-2020 droop-based control.	71
3.9	PVUF (%) at Node-34 and Node-35 with SOCP based ACOPF [25] based control.	71
3.10	PVUF at bus-34 and bus-35 with proposed algorithm-based control.	72
3.11	Positive sequence voltage profile of node-23, node-28 and node-34 with IEEE-1547-2020 droop control.	72

3.12	Positive sequence voltage profile of node-23, node-28 and node-34 with the proposed algorithm-based control.	73
3.13	RPS from SPC_{A35} , SPC_{B35} and SPC_{C35} with the proposed method.	73
3.14	APC and RPS of the TPCs with (a.) proposed method (b.) IEEE 1547-2020	74
3.15	PVUF at bus-35 for the proposed method with the communication delay distributions and data loss.	75
4.1	Case study on voltage of 4 GFM operating in cooperative control. Attacked first conducted a stealth attack at 1.2 s and then an unbalanced attack at 3.2 s	79
4.2	Single-line diagram of N GFM-based cyber physical AC microgrid operating in cooperative control-cyber attack (in brown) launched into local controller of k . . .	79
4.3	Proposed resilient voltage restoration scheme in the k^{th} agent to mitigate stealth/unbalanced attacks in AC microgrid.	84
4.4	Response of 4 GFMs, $\bar{V}_k$ and Q_k^{pu} under (i) balanced attack in GFM-1 at 3.5 s and (ii) attack in agent-2, agent-3, at 5.5 s. Resiliency is achieved using V_2^T	85
4.5	Performance evaluation of the proposed control with varying τ_d of the event-driven resilient signal.	86
4.6	Experimental test bench for the proposed resilient control technique.	86

List of Tables

2.1	Communication delay-distribution between SPVIs to DA	41
2.2	Comparative study of the existing droop control methods for SPVIs in an active LV-ADS system, with the proposed IAPQV droop control.	48
3.1	Data aggregation at i^{th} leader in k^{th} cluster at z^{th} instant	56
3.2	Registration number (ID) and ratings of SPCs	68
3.3	Communication delay distributions and data loss among <i>SPCs</i> and <i>TPCs</i> in intra-clusters	75
3.4	A comparison of the existing methodologies for droop control of SPC/TPC in an LV-ADS system	76
4.1	Comparative evaluation of the proposed resilient methods	87

Nomenclature

Acronyms/Abbreviations

APC Active Power Curtailment

CLFFA Coordinated Leader-Follower Feedback-Based Algorithm

CLFFA Coordinated Leader-Follower Feedback-based Algorithm

CSA Cluster Selection Algorithm

DA Data Aggregator

DB Dead Band

DT Distribution Transformer

HESS Hybrid Energy Storage System

IAPQV Irradiance Adaptive PQV Droop

LV-ADS Low Voltage Active Distribution System

LVUF Local Voltage Unbalance Factor

NREL National Renewable Energy Laboratory

OLTC On-Load Tap Changer

PCC	Point-of-Common-Coupling
PV	Active Power Droop (Volt-Watt)
PVUF	Phase Voltage Unbalance Factor
QV	Reactive Power Droop (Volt-Var)
R/X	Resistance to Reactance Ratio
RMS	Root Mean Square
RPS	Reactive Power Support
SCB	Switched Capacitor Bank
SM	Smart Meter
SPC	Single-Phase Converter
SPVI	Solar Photovoltaic Inverter
TBP	Two-Bit Priority
TPC	Three-Phase Converter
UFQ	Unutilized Reactive Power Ratio
VR	Voltage Regulation