

VOLTAGE STABILITY INVESTIGATIONS IN MODERN POWER SYSTEM

A Thesis submitted to Gujarat Technological University

For the Award of

Doctor of Philosophy

in

Electrical Engineering

by

Sarika Sanjay Kanojia

Enrollment No: 189999914015

Under the supervision of

Supervisor-Dr. Bhavik N. Suthar

&

Co-Supervisor-Dr. Ashutosh K. Giri



GUJARAT TECHNOLOGICAL UNIVERSITY

AHMEDABAD

[September-2026]

VOLTAGE STABILITY INVESTIGATIONS IN MODERN POWER SYSTEM

A Thesis submitted to Gujarat Technological University

For the Award of

Doctor of Philosophy

in

Electrical Engineering

by

Sarika Sanjay Kanojia

Enrollment No: 189999914015

Under the supervision of

Supervisor-Dr. Bhavik N. Suthar

&

Co-Supervisor-Dr. Ashutosh K. Giri



GUJARAT TECHNOLOGICAL UNIVERSITY

AHMEDABAD

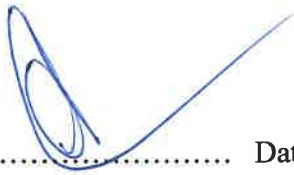
[September-2026]

© [SARIKA SANJAY KANOJIA]

DECLARATION

I declare that the thesis entitled “**Voltage Stability Investigations in Modern Power System**” submitted by me for the degree of **Doctor of Philosophy** is the record of research work carried out by me during the period from 2018 to 2026 under the supervision of **Dr. Bhavik N. Suthar & Dr. Ashutosh K. Giri** and this has not formed the basis for the award of any degree, diploma, associateship, fellowship, titles in this or any other University or other institution of higher learning.

I further declare that the material obtained from other sources has been duly acknowledged in the thesis. I shall be solely responsible for any plagiarism or other irregularities, if noticed in the thesis.



Signature of the Research Scholar: Date: 28/09/2026

Name of Research Scholar: **Sarika Sanjay Kanojia**

Place: Ahmedabad, Gujarat

CERTIFICATE

I certify that the work incorporated in the thesis “**Voltage Stability Investigations in Modern Power System**” submitted by **Sarika Sanjay Kanojia** was carried out by the candidate under my supervision/guidance. To the best of my knowledge: (i) the candidate has not submitted the same research work to any other institution for any degree/diploma, Associateship, Fellowship or other similar titles (ii) the thesis submitted is a record of original research work done by the Research Scholar during the period of study under my supervision, and (iii) the thesis represents independent research work on the part of the Research Scholar.

Signature of the Research Supervisor:  Date: 28/09/2026

Name of Supervisor: **Dr. Bhavik N. Suthar**

Signature of the Research Co- Supervisor:  Date: 28/09/2026

Name of Co-Supervisor: **Dr. Ashutosh K. Giri**

Place: Ahmedabad, Gujarat

Course-work Completion Certificate

This is to certify that **Ms. Sarika Sanjay Kanojia** Enrolment no.**18999914015** is enrolled for PhD program in the faculty **Electrical Engineering Department** of Gujarat Technological University, Ahmedabad.

(Please tick the relevant option(s))

☐ She has been exempted from the course-work (successfully completed during M.Phil. Course)

☐ She has been exempted from Research Methodology Course only (successfully completed during M.Phil. Course)

☒ She has successfully completed the PhD course work for the partial requirement for the award of PhD Degree. His/ Her performance in the course work is as follows-

Grade Obtained in Research Methodology [PH001]	Grade Obtained in Self-Study Course Program [PH002]
BB	AB

Supervisor's Sign



28/09/2026

Dr. Bhavik N. Suthar



28/09/2026

Dr. Ashutosh K. Giri

Originality Report Certificate

It is certified that PhD Thesis titled “**Voltage Stability Investigations in Modern Power System**” by **Sarika Sanjay Kanojia** has been examined by us. We undertake the following:

- a. Thesis has significant new work/knowledge as compared already published rare under consideration to be published elsewhere. No sentence, equation, diagram, table, paragraph or section has been copied verbatim from previous work unless it is placed under quotation marks and duly referenced.
- b. The work presented is original and own work of the author (i.e. there is no plagiarism). No ideas, processes, results or words of others have been presented as Author own work.
- c. There is no fabrication of data or results which have been compiled /analyzed.
- d. There is no falsification by manipulating research materials, equipment or processes, or changing or omitting data or results such that the research is not accurately represented in the research record.
- e. The thesis has been checked using Turnitin (copy of originality report attached) and found within limits as per GTU Plagiarism Policy and instructions issued from time to time (i.e. permitted similarity index $\leq 10\%$).

Signature of the Research Scholar: Date: 28/09/2026

Name of the Research Scholar: **Sarika Sanjay Kanojia**

Place: Ahmedabad, Gujarat

Signature of the Research Supervisor: Date: 28/09/2026

Name of the Research Supervisor: **Dr. Bhavik N. Suthar**

Place: Ahmedabad, Gujarat

Signature of the Research Co- Supervisor: Date: 28/09/2026

Name of the Research Supervisor: **Dr. Ashutosh K. Giri**

Place: Ahmedabad, Gujarat

Copy of Originality Report



Digital Receipt

This receipt acknowledges that Turnitin received your paper. Below you will find the receipt information regarding your submission.

The first page of your submissions is displayed below.

Submission author: Prof.Sarika Kanojia
Assignment title: plag report
Submission title: similarity report
File name: Sarika_Thesis_for_plagiarism_check.pdf
File size: 3.54M
Page count: 179
Word count: 46,149
Character count: 261,839
Submission date: 23-May-2026 10:03PM (UTC+0530)
Submission ID: 2967755671

Submission ID: 2967755671

Submission ID: 2967755671

ABSTRACT

The paper is a review of the current state of the field of plagiarism detection. It discusses the challenges of detecting plagiarism in the digital age, the role of artificial intelligence in plagiarism detection, and the importance of maintaining the integrity of academic research. The paper also discusses the role of plagiarism detection in the legal system and the importance of maintaining the integrity of academic research.

The paper is a review of the current state of the field of plagiarism detection. It discusses the challenges of detecting plagiarism in the digital age, the role of artificial intelligence in plagiarism detection, and the importance of maintaining the integrity of academic research. The paper also discusses the role of plagiarism detection in the legal system and the importance of maintaining the integrity of academic research.

The paper is a review of the current state of the field of plagiarism detection. It discusses the challenges of detecting plagiarism in the digital age, the role of artificial intelligence in plagiarism detection, and the importance of maintaining the integrity of academic research. The paper also discusses the role of plagiarism detection in the legal system and the importance of maintaining the integrity of academic research.

Copy of Originality Report



Page 2 of 102 - Integrity Overview

Submission ID: 135771431.27

8% Overall Similarity

The combined total of all matches, including overlapping sources, for each database

Filtered from the Report

- Bibliography
- Quoted Text
- Cited Text
- Small Matches (less than 5 words)
- Submitted works
- Publications

Exclusions

- 52 Excluded Sources
- 13 Excluded Matches

Match Groups

- **371 Not Cited or Quoted 8%**
Matches with neither in-text citation nor quotation marks
- **0 Missing Quotations 0%**
Matches that are still very similar to source material
- **0 Missing Citation 0%**
Matches that have quotation marks, but no in-text citation
- **0 Cited and Quoted 0%**
Matches with in-text citation present, but no quotation marks

Top Sources

- 8% Internet sources
- 0% Publications
- 0% Submitted works (Student Papers)

Integrity Flags

0 Integrity Flags for Review

No suspicious text manipulations found

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for your review.

A flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.



Page 2 of 102 - Integrity Overview

Submission ID: 135771431.27

Ph.D. Thesis Non-Exclusive License to GUJARAT TECHNOLOGICAL UNIVERSITY

In consideration of being a Ph.D. Research Scholar at Gujarat Technological University, and in the interests of the facilitation of research at the University and elsewhere, I, **Sarika Sanjay Kanojia** having Enrollment no. **189999914015** hereby grant a non- exclusive, royalty free and perpetual license to the University on the following terms:

- a. The University is permitted to archive, reproduce and distribute my thesis, in whole or in part, and/or my abstract, in whole or in part (referred to collectively as the “Work”) anywhere in the world, for non-commercial purposes, in all forms of media;
- b. The University is permitted to authorize, sub-lease, sub-contract or procure any of the acts mentioned in paragraph (a);
- c. The University is authorized to submit the Work at any National/International Library, under the authority of their “Thesis Non-Exclusive License”;
- d. The Universal Copyright Notice (©) shall appear on all copies made under the authority of this license;
- e. I undertake to submit my thesis, through my University, to any Library and Archives. Any abstract submitted with the thesis will be considered to form part of the thesis.
- f. I represent that my thesis is my original work, does not infringe any rights of others, including privacy rights, and that I have the right to make the grant conferred by this non-exclusive license.
- g. If third party copyrighted material was included in my thesis for which, under the terms of the Copyright Act, written permission from the copy right owners is required, I have obtained such permission from the copyright owners to do the acts mentioned in paragraph (a) above for the full term of copyright protection.
- h. I understand that the responsibility for the matter as mentioned in the paragraph (g) rests with the authors / me solely. In no case shall GTU have any liability for any acts / omissions / errors / copyright infringement from the publication of the said thesis or otherwise.
- i. I retain copyright ownership and moral rights in my thesis, and may deal with the copyright in my thesis, in any way consistent with rights granted by me to my University in this non-exclusive license.

- j. GTU logo shall not be used /printed in the book (in any manner whatsoever) being published or any promotional or marketing materials or any such similar documents.
- k. The following statement shall be included appropriately and displayed prominently in the book or any material being published anywhere: “The content of the published work is part of the thesis submitted in partial fulfilment for the award of the degree of Ph.D. in **Electrical Engineering Department** of the Gujarat Technological University”.
- l. I further promise to inform any person to whom I may hereafter assign or license my copyright in my thesis of the rights granted by me to my University in this nonexclusive license. I shall keep GTU indemnified from any and all claims from the Publisher(s) or any third parties at all times resulting or arising from the publishing or use or intended use of the book / such similar document or its contents.
- m. I am aware of and agree to accept the conditions and regulations of Ph.D. including all policy matters related to authorship and plagiarism.

Signature of the Research Scholar: Date: 28/09/2026

Name of Research Scholar: **Sarika Sanjay Kanojia**

Place: Ahmedabad, Gujarat

Recommendation of the Research Supervisor: **Recommended**

Recommendation of the Research Co-Supervisor: **Recommended**

Signature of Supervisor: Date: 28/09/2026

Name of Supervisor: **Dr. Bhavik N. Suthar**

Place: Morbi, Gujarat

Signature of Co-Supervisor: Date: 28/09/2026

Name of Supervisor: **Dr. Ashutosh K. Giri**

Place: Bharuch, Gujarat

Thesis Approval Form

The viva-voce of the PhD Thesis submitted by Ms. Sarika Sanjay Kanodia Enrollment No. 189999914015 entitled "Voltage Stability Investigations in Modern Power System" was conducted on Monday, 28/09/2026 at Gujarat Technological University.

(Please tick any one of the following options)

- ☒ The performance of the candidate was satisfactory. We recommend that she be awarded the PhD degree.
- ☐ Any further modifications in research work recommended by the panel after 3 months from the date of first viva-voce upon request of the Supervisor or request of Independent Research Scholar after which viva-voce can be re-conducted by the same panel again.

(Briefly specify the modifications suggested by the panel)

— NIL —

- ☒ The performance of the candidate was unsatisfactory. We recommend that he/she should not be awarded the PhD degree.

(The panel must give justifications for rejecting the research work)

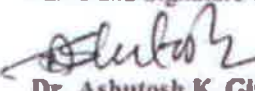
Not applicable

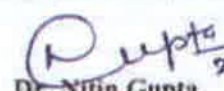

Dr. Bhavik N. Suthar


Dr. Dheeraj Joshi

Name and Signature of Supervisor with Seal

1) (External Examiner1) Name and Signature


Dr. Ashutosh K. Giri 28/9/26


Dr. Nitin Gupta 28/9/26

Name and Signature of Co-Supervisor with Seal

2) (External Examiner2) Name and Signature

ABSTRACT

The rapid electrification of transportation and the large-scale integration of renewable energy sources have significantly transformed modern power distribution systems. While Electric Vehicle Charging Stations (EVCS) and Distributed Generation (DG) based on solar photovoltaic (SPV) and wind energy offers environmental and operational benefits, their uncoordinated integration introduces serious challenges related to voltage stability, power losses, network congestion, and power quality degradation. Maintaining voltage stability under high penetration of EV loads and inverter-interfaced renewable generation has therefore become a critical concern for reliable and secure distribution system operation. Therefore, author have proposed some qualitative approach to address the aforesaid issues and the detailed discussion is provided in the succeeding paragraphs/sections/chapters of this thesis. The authors would like to introduce the entire research work carried out as follows.

This research proposes a comprehensive and integrated approach for voltage stability enhancement in electrical distribution networks by jointly addressing the challenges arising from Electric Vehicle Charging Station (EVCS) integration, renewable distributed generation (DG) penetration, and grid-interfacing control strategies. This approach emphasizes the coordinated planning of network assets to ensure reliable and secure operation under increasing load variability and renewable intermittency. These are discussed here in brief and detailed discussion is provided in forthcoming chapters of this thesis.

First, a novel hybrid Coati Optimization Algorithm-Pelican Optimization Algorithm (COA-POA) is developed to determine the optimal placement of EV charging stations within the distribution system. The optimization problem is formulated with objectives that include minimization of voltage deviation and enhancement of voltage stability indices, thereby directly targeting the most critical operational constraints of distribution networks. By synergistically combining the strong global exploration capability of COA with the efficient local exploitation ability of POA, the proposed hybrid algorithm effectively overcomes common shortcomings of standalone metaheuristic techniques, such as premature convergence, poor diversity, and entrapment in local optima.

This hybrid methodology enables a detailed assessment of the impact of EVCS integration on system voltage profiles, feeder power losses, and overall voltage stability margins. Through systematic simulation studies, this demonstrates how optimal EVCS placement can significantly mitigate adverse effects such as excessive voltage drops and increased losses, while improving network robustness under high EV penetration levels. The obtained results confirm that the hybrid COA-POA approach provides a reliable and efficient solution for planning EVCS deployment in modern distribution networks, contributing to enhanced voltage stability and improved operational performance.

Post-EVCS allocation, Voltage Stability Index (VSI) analysis identifies critical buses exhibiting voltage vulnerability during peak demand periods. Distributed generation (DG) sources are incorporated with EVCS to lessen the impact of EV charging load. Thus, the solar PV and wind-based charging stations will not only reduce the burden on the existing electrical networks but also provides the sustainable, cost effective and eco-friendly environment.

In addition to above, optimal placement of solar PV and wind-based distributed generation units are achieved using the World Cup Optimization (WCO) technique to enhance voltage profile and VSI viz Fast Voltage Stability Index (FVSI), Line Stability Index (LSI), and Line Stability Factor (LSF) are simultaneously incorporated as objective functions to comprehensively assess and enhance the voltage stability of the distribution network. These indices provide quantitative measures of the system's proximity to voltage collapse by evaluating both bus-level and line-level stability margins, thereby enabling accurate identification of critical buses and weak lines under increased loading conditions caused by renewable energy integration. Unlike conventional approaches that rely on a single voltage stability indicator or focus only on voltage magnitude improvement, the proposed multi-index framework ensures a more robust and reliable stability assessment by capturing diverse aspects of voltage instability behaviour across the network.

Therefore, application of WCO in this work, represents a novel contribution, offering a competitive, tournament-based search mechanism that effectively balances global exploration and local exploitation. By integrating FVSI, LSI, and LSF into the WCO approach, the proposed approach efficiently identifies optimal locations for solar PV and wind DG units that significantly improve voltage stability margins, reduce power losses, and enhance overall system performance. This unique combination of multi-index voltage

stability objectives and WCO-based optimization addresses an important research gap and provides a more resilient and scalable solution for modern distribution networks with high penetration of renewable energy sources.

The effectiveness of the proposed methodologies is validated using IEEE 33-bus and IEEE 69-bus distribution test systems through extensive MATLAB/Simulink platform. The results confirm significant improvements in voltage profile, voltage stability indices, and power loss reduction. Overall, the proposed integrated optimization framework provides a practical and reliable solution for enhancing voltage stability, improving renewable hosting capacity, and enabling the secure integration of EVCS and renewable energy sources in modern distribution networks.

Finally, to effectively address the challenges associated with power quality degradation and grid synchronization in grid-connected renewable energy systems, this research develops a Complex Band-Pass Filter based Frequency Locked Loop (CBF-FLL) controller for a dual-stage grid-connected solar photovoltaic (PV) system. The proposed controller is specifically designed to achieve robust and accurate synchronization with the utility grid by reliably extracting fundamental frequency and phase information even in the presence of grid voltage distortions, harmonics, frequency deviations, and voltage imbalances.

The CBF-FLL control strategy enables effective voltage regulation and harmonic mitigation by isolating the fundamental positive-sequence components of grid voltage and current, thereby suppressing the influence of non-linear loads connected at the Point of Common Coupling (PCC). This feature is particularly advantageous under weak grid conditions, where low short-circuit ratios and high grid impedance often deteriorate conventional PLL/FLL-based controller performance. By ensuring stable DC-link voltage regulation and fast dynamic response during transient events such as load changes/ unbalancing, and irradiance variations, the proposed controller enhances the overall stability and reliability of the grid-connected PV system.

The effectiveness of the CBF-FLL controller is validated through extensive simulation studies under diverse operating scenarios, including distorted grid voltages, variable solar irradiance, dynamic load variations, and weak grid environments. Performance evaluation is carried out in terms of total harmonic distortion (THD) of grid voltage and current, DC-link voltage settling time, synchronization accuracy, and transient response. The results

demonstrate that the proposed control strategy maintains THD well within the limits (below 5%) prescribed by IEEE 519 standards thereby ensuring improved power quality, secure grid interaction, and reliable operation of the solar PV system under practical grid conditions. The results in MATLAB/Simulink confirm reduced THD, enhanced voltage control, and robust grid synchronization, ensuring reliable and power quality compliant operation of the system.

Overall, the hybrid COA-POA algorithm achieves optimal EVCS placement for reduced voltage deviation and improved voltage stability, while DG integration using WCO provides additional voltage support and loss reduction. Additionally, the CBF-FLL controller ensures robust synchronization and enhanced power quality, reliability and efficient operation of smart distribution networks.

Acknowledgement

I would like to take this opportunity to devote this research work on “Voltage Stability Investigations in Modern Power System” to the Almighty, God, for providing me an opportunity and strength to pursue a Ph.D. at Gujarat Technology University. I would like to express my sincere gratitude to my supervisor, Prof. (Dr.) Bhavik N. Suthar, Professor, Electrical Engineering Dept., L. E. College, Morbi, for his valuable guidance, encouragement, and insightful suggestions, which were instrumental in the successful completion of this research work.

I am equally and deeply thankful to my co-supervisor, Prof. (Dr.) Ashutosh K. Giri, Assistant Professor, Electrical Engineering Dept., GEC, Bharuch, for his consistent support, valuable technical inputs, and constructive feedback at every stage of this work. His keen insights, thoughtful suggestions, and willingness to share his knowledge greatly enhanced the quality and depth of this research.

I would like to express my sincere regards to Prof. (Dr.) S. R. Joshi, Principal, S & S. S. Gandhi Government Engineering College, Surat & Prof. (Dr.) M. C. Chudasama, Professor, EE, L. D. College of Engineering, Ahmedabad, for their invaluable suggestions and useful feedback during doctoral Progress Committee meetings, it becomes possible for me to reach at this juncture with no difficulties.

My most sincere gratitude with high regards to my parents for providing precious cornerstone at each stage of my life. Their persistent support and ethical values of life, they have inherited in me, helped me a lot to arrive at the final destination of one of the difficult journeys of my life. Finally, I would like to express my heartfelt gratitude to my beloved husband, Sanjay Kanojia, for his unwavering support, understanding, and constant encouragement throughout this journey. His sacrifices and steadfast belief in me have been a source of strength. I am also deeply thankful to my daughter, Pahal, whose joyful presence and affectionate nature brought moments of comfort and balance, helping me rejuvenate and stay motivated. Their love and support have been my greatest source of inspiration and inner strength during the challenges of the past few years. I am grateful to my family for their support throughout this journey. I also thank everyone, mentioned and unmentioned, who has contributed directly or indirectly to this work.

Sarika Sanjay Kanojia (189999914015)

Table of Contents

Abstract	xii
Acknowledgement.....	xvi
List of Abbreviations.....	xxi
List of Symbols	xxiii
List of Figures	xxvii
List of Tables.....	xxx
List of Appendix.....	xxxi
 Chapter-1 Introduction	 1
1.1 Background.....	1
1.2 Modern Power System Structure	2
1.3 Concept of Voltage Stability.....	3
1.3.1 Voltage Instability Mechanism.....	4
1.3.2 Types of Voltage Stability	4
1.3.3 Causes of Voltage Instability.....	5
1.3.4 Voltage Stability Indices (VSIs)	5
1.4 Major Contributors of Voltage Instability in Modern Distribution System	6
1.4.1 Rapid Growth of Electric Vehicle Charging Stations (EVCS).....	6
1.4.2 High Penetration of Renewable Energy Sources (RES).....	7
1.4.3 Lack of Dynamic VAR Support	7
1.4.4 Uncertainty in Distributed Energy Resources (DERs)	7
1.5 Role of Electric Vehicle Charging Stations (EVCS).....	7
1.6 Voltage Stability Issues with EVCS Load in Distribution System.....	9
1.7 Voltage Stability Problem in Renewable-Dominated Systems	11
1.8 Integration of Renewable Energy for Voltage Stability Enhancement.....	12
1.9 Advanced Control Techniques for Grid Integration	12
1.10 Observation.....	12
1.11 Motivation.....	13
1.12 Rationale of Research	14
1.13 Organization of the Thesis.....	15

Chapter -2 Literature Survey	17
2.1 Review on Voltage Stability Indices in Renewable-Rich Systems	17
2.1.1 Voltage Stability Index Need for Renewable Integration.....	19
2.1.2 Voltage Collapse Point Detection.....	21
2.2 Comparison of VSI/Classification	23
2.2.1. Load Flow using Jacobian Singularity.....	24
2.2.2 P-V and Q-V Curves Load Margin [55]-[57]	25
2.2.3 Maximum Power Transfer Theorem.....	26
2.2.4 Power Transferable Limit of a Transmission Line	26
2.2.5 Lyapunov Based Stability Theory	27
2.3 Cyber-Physical and ML-Based VSI Methods	34
2.4 Literature Review on Optimal EVCS Placement	35
2.4.1 Practical Challenges and Solutions in EVCS Placement.....	40
2.5 Literature Review on Impact of DG Placement.....	41
2.5.1. Influence of Cable Material and Feeder Characteristics on Loss Reduction.....	44
2.5.2. Limitations of Tap Changers and Advantages of DG-Based Voltage Support	45
2.6 Literature Review for Inverter Based Renewable Energy Integration.	46
2.7 Challenges and Directions for Future Research	50
2.8 Summary of Literature Review.....	51
2.9 Research Gap	52
2.10 Research Objectives.....	53
2.11 Author's Contribution.....	53
2.12 Original Contributions of the Thesis	54
2.13 Summary.....	54
Chapter–3 Optimal EVCS Placement Using Hybrid Optimization	56
3.1 Introduction.....	56
3.2 Problem Statement-1.....	58
3.3 Proposed Methodology	59
3.3.1 Proposed Methodology for Problem Statement-1	60
3.3.2 Coati Optimization Algorithm (COA)- Exploration Phase (Global Search) [140]	60
3.3.3 Pelican Optimization Algorithm (POA)- Exploitation Phase (Local Search) [141] ..	60
3.3.4 Hybrid COA- POA (Proposed).....	61
3.4 EV Charging Station Modelling	61

3.5 Hybrid Optimization Algorithm for Placement of EV Charging Station	62
3.6 Results and Discussion with Random and Optimal EVCS Placement	67
3.7 Summary	74
Chapter- 4 Optimal DG Placement for Voltage Stability Enhancement	75
4.1 Introduction.....	75
4.2 Problem Statement-2.....	76
4.3 Proposed Methodology for Problem Statement-2	76
4.4 Solar and Wind Modelling.....	77
4.5 World Cup Optimization Algorithm.....	77
4.6 Results with Random EVCS, Optimal EVCS and PV Placement.....	84
4.6.1 The Results of IEEE 33 bus Distribution System with Optimal PV Placement.....	84
4.6.2 Validation using IEEE-69 bus Radial Distribution System.....	89
4.6.3 Results and Discussion with EVCS, PV and with Varying Load Condition.....	98
4.6.4 Results and Discussion with Optimal Placement of EVCS, PV and Wind	108
4.7 Summary	112
Chapter - 5 CBF-FLL Based Grid Integration of Solar PV for Voltage & Power Quality Improvement	114
5.1 Introduction.....	114
5.2.Problem Statement-3.....	117
5.3 Proposed Methodology for Problem Statement-3	117
5.4 Grid Tied Solar PV System Configuration	119
5.5 Design of Solar PV System	120
5.5.1 PV Array Configuration.....	120
5.5.2 Boost Converter Design.....	121
5.5.3 Selection of Interfacing Inductor	122
5.5.4 Selection of DC-Link Capacitor	122
5.5.5 Grid Specifications	122
5.5.6 Load Configuration at PCC	123
5.6 Control Technique	123
5.6.1 MPPT Algorithm	123
5.6.2 VSC Control	124
5.6.4 Evaluation of SPV Instantaneous & DC Loss Components.....	127
5.6.5 CBF-FLL Control System	127

5.6.6 Estimation of Reference Grid Current	131
5.7. Simulation Results and Discussion.....	132
5.7.1 Simulation Response Under Steady Condition with Non-Linear Load.....	132
5.7.2 Simulation Response Under Change in Irradiance	134
5.7.3. Simulation Response with Step Increase and Decrease in Non-Linear Load.....	136
5.7.4. Simulation Response During Night Time or Zero Irradiation.	139
5.7.5 Unbalancing in Load (One Phase Open)	141
5.7.6 Simulation Response Under Strong and Weak Grid Condition	143
5.8 Comparative Analysis.....	146
5.9 Summary.....	148
Chapter- 6 Conclusion And Future Scope	150
6.1 Conclusion	150
6.2. Scope of the Future Work.....	153
References	154
Patent Detail	170
List of Publications	171
A. Journal Papers Published.....	171
B. Conference Papers/ Book Chapter Published	171
C. Journal Papers Communicated.....	172
APPENDIX-A	173
APPENDIX-B	176

List of Abbreviations

SPV	Solar Photovoltaic
DG	Distributed Generation
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
FAME	Faster Adoption and Manufacturing of EV in INDIA
COA	Coati Optimization Algorithm
POA	Pelican Optimization Algorithm
WCO	World Cup Optimization
PSO	Particle Swarm Optimization
GA	Genetic Algorithm
HSA	Harmony Search Algorithm
VSI	Voltage Stability Index
FVSI	Fast Voltage Stability Index
MPT	Maximum Power Transfer
LSI	Line Stability Index
LSF	Line Stability Factor
CBF	Complex Band-Pass Filter
FLL	Frequency Lock Loop
PLL	Phase Lock Loop
PCC	Point Of Common Coupling
THD	Total Harmonic Distortion
RES	Renewable Energy Sources
CS	Charging Station
VAR	Volt Ampere Reactive
OLTC	On Load Tap Changer
DER	Distributed Energy Resources
GFL	Grid Following
DISCOM	Distribution Company
VCPI	Voltage Collapse Proximity Index
DFIG	Doubly Fed Induction Generator
PSI	Preference Selection Index

DSVS	Dynamic System Voltage Stability
Dstatcom	Distribution Static Synchronous Compensator
HGP_CS	Hybrid GWO, PSO, and Cuckoo Search optimization
IEEE	Institute of Electrical and Electronics Engineers
G2V	Grid-to-Vehicle
V2G	Vehicle-to-Grid
VS	Voltage Stability
LSF	Loss Sensitivity Factor
LC	Least Cost Analysis Algorithm
OPF	Optimal Power Flow
CHP	Combined Heat and Power
FIFA	Fédération Internationale de Football Association
SOGI-FLL	Second-Order Generalized Integrator
SCR	Short Circuit Ratio
D-SOGI	Dual-Second Order Generalized Integrator
BES	Battery Energy Storage
ICCF-PLL	Improved Complex Coefficient Filter-Phase Lock Loop
HVDC	High Voltage Direct Current
WECS	Wind Energy Conversion System
FACT's	Flexible Alternating Current Transmission System
LPTC	Line Power Transfer Capability
MPTTTL	Maximum Power Transferable Through a Transmission Line
PMU	Phasor Measurement Unit
ML	Machine Learning
LTVS	Long Term Voltage Stability
DNN	Deep Neural Network
ULQF	Unified Loadability Quality Factor
LIMM	Load Impedance Modulus Margin
DSVS	Dynamic System Voltage Stability Index
VSC	Voltage Source Converter
SOC	State of Charge
LTVS	Long Term Voltage Stability

List of Symbols

D	Energy demand
E_{EV}	Total energy required for to EV
N_k	Number of vehicles
N_{EV}	Indicates number of EVs
N_C	Denotes number of chargers available in charging station
$P_{\min}$	Signifies minimum power
$P_{\max}$	Represent maximum power
SOC_i	Indicates SOC of i^{th} EV
$SOC_{\min i}$	Denotes minimum SOC
$SOC_{\max i}$	Represent maximum SOC
N_n	Indicates number of nodes in IEEE 33 system
V_a	Node a voltage
V_b	Denotes node b voltage
P_b	Indicates active power
X_{ab}	Reactance in branches
Q_b	Represent reactive power
R_{ab}	Resistance between nodes a and b
m	Means total decision variables
C_i	Indicates bus position in i^{th} search space
R	Random number
C_{ij}	j^{th} Decision variable
N	Number of buses
$C_{i,j}^{P2}$	Updated position based on POA exploitation phase
t	Iteration counter
T	Maximum number of iterations
F_i^{P2}	An updated objective function
f	Combined hybrid objective function.
f_1	First objective function representing the minimization of voltage deviation in distribution system

f_2	Second objective function representing the maximization of the voltage stability index (VSI) for improving system stability
W	Weighting factor used to balance the contribution of both objective functions in the hybrid optimization process.
$U_j \& L_j$	represents upper and lower bound of the j^{th} variable
W	represents the population structure used in the World Cup Optimization (WCO) algorithm
$W_{i,j}$	represents the value of the j^{th} optimization variable for the i^{th} candidate solution
$P_{pv}(t)$	Indicates PV power
A	Area of solar panel placement
η	PV panel's efficiency
$\mu(t)$	Irradiance of solar
$P_{wind}(t)$	Power obtained from wind turbine
A	Area swept by wind turbine
ρ	Air density
v	Wind speed
C_p	Power Coefficient
M	Total iterations
X	Inductive reactance
Q_R	Reactive power
V_S	Sending end voltage
α	Angle at sending end
β	Angle at receiving end
P_S	Active power at sending end
Z	Line impedance
R	Ranking
χ	Increasing or decreasing values
σ	Standard deviation
W_i	Population value
$\overline{W}$	Mean value
n	Number of populations
W_{new}	New population matrix

W_{best}	Best obtained value
W_{Rand}	Random value
A	Accuracy parameter
u	Upper bound
l	Lower bound
V_{oc}	Open circuit voltage
I_{sc}	Short circuit current
V_{mp}	Voltage of solar panel at maximum power point
I_{mp}	Current of solar panel at maximum power point
N_s	No. Of series modules per string
N_p	No. Of parallel string
P_{mp}	Maximum power
$V_{mp(array)}$	Voltage at MPP array
$I_{mp(array)}$	Current at MPP array
$P_{mp(array)}$	Rated array power
V_{in}	Boost converter input voltage
V_{out}	Boost converter output voltage
f	Switching frequency
P	Power of boost converter
D	Duty cycle
I_{in}	Boost converter input current
Δi_L	Acceptable current ripple limits in the PV system
m	Modulation index
L_f	Interface inductor
V_{dc}	DC link voltage
h	Overloading factor
Δi	Ripple in inductor current
Δv_c	Ripple in voltage
C_{dc}	DC link capacitor
R	Resistance
L	Inductance
I_{fa}	Fundamental current component
I_{peak}	Peak current

V_{ab}, V_{bc}	Line to line voltage
V_a, V_b, V_c	Phase voltages
V_t	Peak amplitude of the phase voltage
u_{pa}, u_{pb}, u_{pc}	The in-phase unit templates
u_{qa}, u_{qb}, u_{qc}	Quadrature unit templates
I_{pv}	Solar photovoltaic system's instantaneous compensation term
I_{pdc}	Loss component
K_p	Proportional gain
K_i	Integral gain
ω_p	CBF cutoff frequency (bandwidth)
ω_g	Nominal grid angular frequency
V_{dc}^*	DC voltage reference value
$I_{fp(a,b,c)}$	Load currents' fundamental component
I_{dT}	Net active power component of the grid current
$i_{ga}^*, i_{gb}^*, i_{gc}^*$	In-phase reference currents
$i_{ga}^e, i_{gb}^e, i_{gc}^e$	Error signal of grid current
i_g^*	Reference grid current
i_g	Actual grid current
V_{gabc}	Grid voltages at PCC
I_{gabc}	Grid current
I_{Labc}	Load current
$V_{inv-abc}$	VSC Voltage
V_{pv}	PV array voltage
I_{pv}	PV array current
P_{pv}	PV power output
P_{grid}	Grid power
P_{load}	Load power
P_{inv}	Inverter power
P_{solar}	Solar power
$V_s \angle \delta_s$	Sending end bus Voltage
$V_r \angle \delta_r$	Receiving end bus Voltage

$\Delta P, \Delta Q$	change in active and reactive powers respectively
$\Delta V, \Delta \theta$	change in voltage and load angle respectively
J	Jacobian matrix
$P_s + jQ_s$ & $P_r + jQ_r$	Sending and receiving end real and reactive powers
R, X, Y	Resistance, inductive reactance and shunt half line charging admittance of transmission line respectively.

List of Figures

Figure 2. 1 Voltage stability comparison with renewable dominated power system	20
Figure 2. 2 Two bus power system representation	22
Figure 2. 3 Classification of voltage stability methods	24
Figure 2. 4 (a) P-V curve (b) Q-V curve.....	25
Figure 2. 5 Thevenin's equivalent circuit	26
Figure 2. 6 Two bus transmission line model	27
Figure 2. 7 Line model with shunt admittance	27
Figure 2. 8 Voltage Collapse recognition criterion.....	27
Figure 3. 1 Flowchart for hybrid COA-POA.....	66
Figure 3. 2 IEEE 33 distribution network with optimal & random EVCS placement	68
Figure 3.3: Voltage Profile (a) base case (b) with random EVCS location (c) with optimal EVCS location	70
Figure 3. 4 Active power loss	70
Figure 3. 5 Reactive power loss.....	71
Figure 3. 6 Total Power loss	71
Figure 3. 7 Comparison of proposed hybrid algorithm	73
Figure 4. 1 Basic Flowchart of WCO Algorithm [182].....	79
Figure 4. 2 Flowchart for WCO algorithm for optimal placement of DG.....	83
Figure 4. 3 IEEE 33 distribution network with optimal EVCS, PV and Wind	84
Figure 4. 4 (a) Voltage profile (b) Active power loss and (c) reactive power loss.....	86
Figure 4. 5 Comparison of total losses for IEEE 33 bus system	88
Figure 4. 6 IEEE 69 bus distribution network with random and optimal EVCS and PV	89
Figure 4. 7 Voltage profile of IEEE 69 bus for various cases	90
Figure 4. 8 Active power loss of IEEE 69 bus for various cases.....	91
Figure 4. 9 Reactive power loss of IEEE 69 bus for various cases	91
Figure 4. 10 VSI's for 69 bus IEEE system (a) Line Stability Factor (b) Fast Voltage Stability Index (c) Line Stability Index.....	94
Figure 4.11 Comparison of total losses	94
Figure 4. 12 Voltage Profile	99
Figure 4. 13 Comparison of reactive power loss	99

Figure 4. 14 Comparison of active power loss	100
Figure 4. 15 Convergence Comparison WCO Vs PSO	107
Figure 4. 16 Voltage profile for various cases.....	108
Figure 4. 17 Active power loss	109
Figure 4. 18 Reactive power loss.....	109
Figure 4. 19 VSI's for 33 IEEE system (a) Line Stability Factor (b) Fast Voltage Stability Index (c) Line Stability Index.....	111
Figure 4. 20 Comparison of total losses	111
Figure 4. 21 Comparison of proposed algorithm.....	112
Figure 5. 1 Proposed dual stage solar PV system connected to grid	119
Figure 5. 2 I-V and P-V characteristics of Solar PV array	120
Figure 5. 3 InC MPPT characteristics.....	124
Figure 5. 4 Control Structure based on CBF- FLL	125
Figure 5. 5 Bode Plot of CBF-FLL.....	130
Figure 5. 6 Response under steady state with non-linear load (a) Solar PV parameters (b) Grid and load side waveforms (c) Power balance	134
Figure 5. 7 Response under varying irradiances with non-linear load (a) Solar PV parameters (b) Grid and load side waveforms (c) Power balance	136
Figure 5. 8 Response with step increase in non-linear load (a) Grid and load side waveforms (b) Power balance (c) harmonic spectrum.....	138
Figure 5. 9 Response with step decrease in non-linear load (a) Grid and load side waveforms (b) Power balance	139
Figure 5. 10 Response under zero irradiation (a) Solar PV parameters (b) Grid and load side waveforms (c) Power balance	141
Figure 5. 11 Response under zero irradiation (a) Grid and load side waveforms (b) Power balance	142
Figure 5. 12 Response of grid and load side waveforms under (a) weak grid (b) strong grid condition	144
Figure 5. 13 Harmonic spectrum under (a) strong grid (b) weak grid.....	146
Figure 5. 14 Comparative analysis between LMS-FLL and proposed CBF-FLL	147

List of Tables

Table 2. 1 Overview of several ways of operation with varied generation	21
Table 2. 2 Voltage stability indices based on Jacobian Matrix	22
Table 2. 3 Line voltage stability indices	29
Table 2. 4 Bus voltage stability indices	31
Table 2. 5 Overall voltage stability indices	34
Table 3. 1 Simulation Parameter for EVCS and hybrid optimization method.	67
Table 3. 2 EV Battery Specification	68
Table 3. 3 Comparative analysis.....	72
Table 4. 1 PV and wind parameter specification	85
Table 4. 2 Comparative analysis of IEEE 33 and 69 bus system performance	95
Table 4. 3 Comparative outcomes of the suggested approach with references to relevant literature.....	98
Table 4. 5 Comparative analysis of various VSIs evaluated for base case.....	100
Table 4. 6 Comparative analysis for VSI'S evaluated for Optimal placement (PSO technique) of PV on 28 th bus in IEEE-33 bus system.	101
Table 4. 7 Comparative analysis for VSI'S evaluated for Optimal placement (WCO technique) of PV on 26 th bus in IEEE-33 bus system.	103
Table 4. 8 Comparative analysis of VSI's assessed at 125% of the system base case.....	104
Table 4. 9 Comparative analysis of VSI's assessed at 150% of the system base case.....	105
Table 4. 10 Comparative analysis of total losses for various cases	106
Table 4. 11 Power loss comparison of WCO with literature methods in IEEE 33-bus system	107
Table 5. 1 Parameters of 775 kW solar array	121
Table 5. 2 Performance comparison of synchronization techniques for grid-connected PV inverters [230]	128
Table 5. 3 Dynamic performance comparison of LMS-FLL and proposed CBF-FLL	148

List of Appendix

Appendix A: 1) IEEE 33 bus system data

3) IEEE 69 bus System data

4) System data for Solar PV and CBF-FLL controller

Appendix B: 1) Pseudo code for Hybrid COA-POA method for optimal EVCS placement

2) Pseudo code for optimal DG placement using WCO method

Chapter-1 Introduction

1.1 Background

The rapid transformation of modern power systems is driven by increasing electricity demand, large-scale integration of renewable energy sources (RES), and the widespread adoption of electric vehicles (EVs). While these developments support global decarbonization and sustainability goals, they also introduce significant technical challenges related to voltage regulation, power quality, and system stability. Among these challenges, voltage stability has emerged as a critical concern for the reliable and secure operation of distribution and transmission networks.

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. Failure to maintain voltage stability may lead to progressive voltage drops, equipment malfunction, load shedding, and, in severe cases, large-scale blackouts. Several major grid disturbances in India, including the 2012 Northern Grid blackout and the 2020 Mumbai outage, have highlighted the vulnerability of stressed power systems to voltage instability, especially under high loading and limited reactive power support.

In recent years, the penetration of renewable energy sources, particularly solar photovoltaic (PV) and wind power, has increased rapidly due to declining costs, environmental benefits, and supportive government policies. However, the intermittent and uncertain nature of renewable energy sources (RES) generation, coupled with inverter-based interfacing, alters traditional power flow patterns and reduces system inertia. These factors significantly impact voltage stability margins, especially in weak and radial distribution networks.

Simultaneously, the growing deployment of Electric Vehicle Charging Stations (EVCS) introduces high and impulsive loads into the distribution system. Unplanned or poorly located EVCS can lead to excessive voltage drops, feeder overloading, increased power losses, and degraded power quality. The clustering of fast-charging stations further exacerbates these issues, making optimal EVCS placement a crucial planning and operational problem for utilities. Traditional planning approaches are inadequate to address

the complex, multi-objective nature of EVCS integration, which involves voltage deviation minimization, stability enhancement, and loss reduction.

To address these challenges, optimization-based planning techniques have gained significant attention. However, conventional optimization algorithms often suffer from premature convergence, poor exploration capability, or excessive computational burden when applied to large-scale, non-linear, and multi-objective power system problems. Hybrid metaheuristic algorithms, which combine the strengths of different optimization techniques, offer a promising solution by effectively balancing global exploration and local exploitation.

In addition to planning-level challenges, real-time voltage control and power quality enhancement are essential for grid-connected renewable systems. Grid-following inverters, commonly used in PV systems, rely heavily on accurate synchronization with the grid. Conventional Phase-Locked Loop (PLL) based synchronization methods exhibit poor performance under distorted grid conditions, voltage unbalance, and harmonic distortion. Advanced synchronization techniques such as Frequency Locked Loop (FLL)-based controllers have shown improved robustness and dynamic performance, making them suitable for modern distribution systems with high penetration of RES and non-linear loads.

1.2 Structure of Modern Power System

Modern power systems have evolved significantly from traditional centralized architectures to decentralized, intelligent, and highly dynamic networks. This transformation is primarily driven by the large-scale integration of distributed generation (DG), renewable energy sources (RES), and advanced communication technologies.

One of the defining features of modern power systems is bidirectional power flow. In conventional systems, power flows unidirectionally from generation → transmission → distribution → consumers. However, with the integration of rooftop solar PV, wind generators, and other distributed sources at the distribution level, power can now flow in multiple directions. This creates challenges in protection coordination, voltage regulation, and system monitoring.

Another key characteristic is the high penetration of renewable energy sources such as solar and wind. These sources are inherently intermittent and dependent on environmental conditions, introducing variability and uncertainty into power generation. Unlike

conventional generators, RES lacks controllability and predictability, making system operation more complex.

Modern grids also rely heavily on power electronic converters, which interface renewable generation, energy storage systems, and EV chargers with the grid. While these converters enable efficient energy conversion and control, they also introduce harmonics, reduce system inertia, and affect voltage stability.

The integration of smart grid technologies has further enhanced system observability and controllability. Advanced Metering Infrastructure (AMI), Phasor Measurement Units (PMUs), and communication networks enable real-time monitoring, automation, and decision-making. However, this also increases system complexity and dependence on cyber-physical infrastructure.

Additionally, modern loads exhibit dynamic and stochastic behaviour. The increasing use of Electric Vehicle Charging Stations (EVCS), power electronics loads, and automated systems leads to rapid and unpredictable variations in demand. These nonlinear loads contribute to harmonics and voltage fluctuations.

Overall, these features introduce uncertainty, nonlinearity, and fast dynamics, which directly impact system stability, especially voltage stability, making it a critical area of study in modern power systems.

1.3 Concept of Voltage Stability

Voltage stability is a fundamental aspect of power system operation and is defined as the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition.

At its core, voltage stability is governed by the balance between reactive power supply and demand. Reactive power plays a crucial role in maintaining voltage levels across the network. When the system is unable to meet the reactive power demand, voltage levels begin to drop, potentially leading to instability.

1.3.1 Voltage Instability Mechanism

Voltage instability occurs when:

- Load demand increases beyond system capability
- The system cannot provide sufficient reactive power support
- Transmission constraints limit reactive power transfer

This results in a progressive decline in voltage magnitude, which may ultimately lead to voltage collapse, causing partial or complete system blackout.

1.3.2 Types of Voltage Stability

Voltage stability can be broadly classified into two categories:

1. Short-Term Voltage Stability

- Associated with fast dynamics (milliseconds to seconds)
- Influenced by:
 - Induction motors
 - Power electronic converters
 - HVDC and FACTS devices
- Critical during faults and sudden disturbances.

2. Long-Term Voltage Stability

- Involves slow dynamics (seconds to minutes)
- Influenced by:
 - Tap-changing transformers (OLTC)
 - Load recovery characteristics
 - Generator reactive power limits
- Determines system behavior over extended periods.

1.3.3 Causes of Voltage Instability

Several factors contribute to voltage instability in power systems:

- Sudden Increase in Load Demand- Rapid or unexpected load growth increases reactive power demand, which may exceed system capability.
- Insufficient Reactive Power Support- Lack of reactive power sources such as capacitors, generators, or FACTS devices leads to voltage drops.
- Long Transmission Distances- Reactive power losses increase with distance, reducing voltage at receiving ends.
- Outage of System Components- Failure of transmission lines, generators, or transformers disrupts power flow and voltage balance.
- High Penetration of Renewable Energy Sources- RES provides limited reactive support and introduce variability, weakening voltage control.

1.3.4 Voltage Stability Indices (VSIs)

Voltage Stability Indices (VSIs) are important analytical tools used to evaluate the stability condition of a power system and to determine how close the system is to voltage collapse. These indices are derived from system parameters such as bus voltages, line flows, and power transfer conditions, and provide a quantitative measure of voltage stability margin. VSIs are extensively used in both transmission and distribution systems to identify weak buses, critical lines, and stressed operating conditions, enabling timely corrective actions.

In practical power system operation, especially with the increasing penetration of renewable energy sources and dynamic loads, continuous monitoring of voltage stability becomes essential. VSIs offer an effective solution by providing fast and reliable assessment without requiring extensive computational effort. Many indices are formulated using simplified system models, making them suitable for real-time implementation using data from measurement devices such as Phasor Measurement Units (PMUs).

One of the key advantages of VSIs is their simple computation. Most indices are based on algebraic expressions involving readily available parameters like voltage magnitude, current, and power flow. This simplicity allows them to be easily integrated into load flow programs and real-time monitoring systems without adding significant computational burden, even for large-scale power networks.

Another significant benefit is their real-time applicability. Since VSIs require minimal computational resources and can utilize real-time measurement data, they are well-suited for online stability monitoring. System operators can continuously track the stability status and receive early warning signals when the system approaches critical limits. This enables proactive control actions such as reactive power compensation, load shedding, or network reconfiguration.

VSIs are also highly effective in the identification of weak locations within the power system. By evaluating the index values across buses and transmission lines, it is possible to pinpoint the most vulnerable areas that are prone to voltage instability. These weak buses or lines can then be prioritized for corrective measures, such as the placement of distributed generation (DG), FACTS devices, or capacitor banks to enhance voltage stability.

Furthermore, VSIs play a crucial role in optimization and planning studies, where they are used as objective functions or constraints for problems such as optimal placement of distributed generation, EV charging stations, and reactive power compensation devices. Their ability to provide clear and interpretable stability information makes them valuable for both operational and research applications.

In summary, Voltage stability indices offer a computationally efficient, real-time, and practical approach for assessing voltage stability in modern power systems. Their capability to identify weak points and provide early indications of instability makes them indispensable tools for ensuring secure and reliable system operation.

1.4 Major Contributors of Voltage Instability in Modern Distribution System

1.4.1 Rapid Growth of Electric Vehicle Charging Stations (EVCS)

- High, impulsive, and clustered charging demand.
- Simultaneous charging causes sudden load peaks on distribution feeders.
- Increases harmonics, impacting voltage quality.
- Also, the random placement of electric vehicle charging station (EVCS) adversely affects the acceptance of charging station (CS).
- If the placement of CS is not done properly, then fluctuation in voltages and power problems arises.

- The placing of the CS causes increases in demand for the load on the power grid, which results in an increase in peak demand and a decrease in reserve margin.
- Numerous studies are being conducted across different countries of the world for developing EVCS.

1.4.2 High Penetration of Renewable Energy Sources (RES)

- Intermittent and unpredictable generation (solar & wind).
- Reduction in system inertia and short-circuit strength.
- Inverter-based resources provide limited reactive power support.
- Sudden drop in generation during cloud cover or wind speed variations.

1.4.3 Lack of Dynamic VAR Support

- Conventional generating units operating at reduced MVAR capability.
- Inverter-based resources not providing adequate dynamic support.
- Delay or malfunction in on load tap changers (OLTC).

1.4.4 Uncertainty in Distributed Energy Resources (DERs)

- Localized overvoltage/undervoltage due to mismatch of generation and load.
- Poorly controlled microgrids interfacing with the main grid.

1.5 Role of Electric Vehicle Charging Stations (EVCS)

The rapid adoption of electric vehicles (EVs) across the globe has necessitated the large-scale deployment of Electric Vehicle Charging Stations (EVCS) within existing power distribution networks. While EVs contribute to reduced carbon emissions and sustainable transportation, their integration introduces new operational challenges to power systems. EVCS behave as high-power, time-varying, and nonlinear loads, which significantly influence the performance, reliability, and stability of distribution systems.

One of the primary impacts of EVCS is the increase in peak load demand. Fast-charging stations, in particular, draw substantial power from the grid within short durations. When multiple EVs are charged simultaneously especially during peak hours, this leads to sudden spikes in load demand. Such clustered charging behavior can strain the distribution infrastructure, forcing utilities to operate closer to their capacity limits and reducing the available reserve margin.

Another critical concern is the voltage drop in distribution feeders. EVCS are often installed at locations far from substations, such as residential areas, commercial hubs, or highway corridors. The high current drawn by EV chargers increases the voltage drop along the feeder due to line impedance. This results in reduced voltage levels at downstream buses, potentially violating permissible voltage limits and affecting the quality of supply to other consumers connected to the same feeder.

The integration of EVCS also contributes to line overloading. Distribution lines and transformers are typically designed based on conventional load patterns. The additional load imposed by EV charging, particularly under uncoordinated scenarios, can exceed the thermal limits of these components. Persistent overloading may lead to overheating, accelerated aging of equipment, and increased risk of failures, thereby compromising system reliability.

EVCS further contribute to the deterioration of voltage stability. The high and fluctuating power demand, combined with the stochastic nature of EV charging behavior, introduces uncertainty into the system. During heavy loading conditions, the system may struggle to maintain acceptable voltage levels, especially in weak grids with limited reactive power support. This increases the likelihood of voltage instability or even voltage collapse in extreme cases.

In addition, EV chargers being power electronic devices introduce harmonics and power quality issues into the system. Nonlinear charging characteristics can distort current waveforms, leading to increased Total Harmonic Distortion (THD). This not only affects voltage quality but also causes additional losses, overheating, and interference with sensitive equipment.

A major challenge arises from the uncoordinated and random placement of EVCS. Without proper planning, EVCS may be installed at electrically weak buses or heavily loaded feeders, exacerbating existing issues such as voltage deviation and power losses. Random placement can lead to uneven load distribution, poor voltage profiles, and inefficient utilization of network resources.

Moreover, the interaction of EVCS with other emerging elements such as renewable energy sources (RES) add further complexity. While RES introduces variability on the generation side, EVCS introduces variability on the demand side. This dual uncertainty creates highly

dynamic operating conditions, making real-time monitoring and control of voltage stability more challenging.

To address these challenges, optimal placement of EVCS have become essential. Strategic allocation of charging stations based on technical criteria such as Voltage Stability Indices (VSI), power loss minimization, and voltage deviation can significantly enhance system performance. Advanced optimization techniques and smart grid technologies can be employed to identify suitable locations that minimize adverse impacts while maximizing system efficiency.

Furthermore, the adoption of smart charging strategies, such as time-of-use pricing, demand response, and vehicle-to-grid (V2G) integration, can help mitigate the negative effects of EVCS. These approaches enable better coordination between EV demand and grid conditions, reducing peak load stress and improving voltage stability.

In summary, while EVCS are crucial for supporting the transition to electric mobility, their integration poses significant challenges to power system operation. Issues such as increased peak demand, voltage drops, line overloading, and voltage instability must be carefully managed through optimal planning and advanced control strategies. Properly designed EVCS integration not only minimizes adverse impacts but also enhances the overall efficiency, reliability, and stability of modern power distribution systems.

1.6 Voltage Stability Issues with EVCS Load in Distribution System

The integration of Electric Vehicle Charging Stations (EVCS) into distribution systems introduces significant challenges to voltage stability due to their high-power demand, stochastic behaviour, and nonlinear characteristics. As EV adoption increases, the cumulative impact of charging loads becomes more pronounced, particularly in radial distribution networks with limited capacity.

One of the major concerns is the sudden and high-power demand associated with EV charging. Fast-charging stations draw large amounts of power in a short duration, and when multiple vehicles charge simultaneously, it leads to load clustering. This results in sharp increases in demand, causing voltage drops along the feeder, especially at buses located far from the substation.

Another critical issue is the uncoordinated and random charging behaviour of EVs. Since charging depends on user habits, time of day, and travel patterns, it introduces uncertainty into the load profile. This stochastic nature makes it difficult to predict system conditions, leading to fluctuating voltage profiles and increased risk of voltage instability.

EVCS also contribute to line and transformer overloading. Distribution infrastructure is generally designed for conventional load patterns, and the additional EV load can exceed thermal limits. Overloaded lines experience higher current flow, which increases voltage drops due to line impedance, further degrading voltage stability.

The reactive power imbalance is another important factor. EV chargers, particularly fast chargers, may operate at non-unity power factor and draw reactive power from the grid. In systems with limited reactive power support, this leads to insufficient voltage regulation, making the system more prone to instability.

In addition, EV chargers are based on power electronic converters, which introduce harmonics into the system. These harmonics distort voltage and current waveforms, increasing Total Harmonic Distortion (THD) and negatively affecting power quality. Poor power quality can indirectly impact voltage stability and system reliability.

The problem becomes more severe in weak distribution networks, where the short-circuit capacity is low. In such systems, even small increases in EV load can cause significant voltage deviations. When combined with high penetration of renewable energy sources, the system experiences dual uncertainty from both generation and load sides, further complicating voltage stability management.

Moreover, the location of EVCS plays a crucial role. If charging stations are installed at electrically weak buses or heavily loaded feeders without proper planning, they can significantly worsen voltage profiles and increase system losses. This highlights the importance of optimal placement and sizing of EVCS based on technical criteria such as voltage stability indices (VSI).

In summary, EVCS integration leads to multiple voltage stability challenges, including voltage drops, load uncertainty, reactive power imbalance, harmonic distortion, and overloading of network components. To mitigate these issues, it is essential to adopt

optimized planning strategies, smart charging techniques, and advanced control methods, ensuring stable and reliable operation of modern distribution systems.

1.7 Voltage Stability Problem in Renewable-Dominated Systems

The integration of renewable energy sources (RES) into modern power systems introduces significant variability and uncertainty due to their dependence on environmental conditions such as solar irradiance and wind speed. This intermittent nature of generation leads to continuous fluctuations in power output, making voltage regulation more challenging. Unlike conventional synchronous generators, inverter-based renewable sources contribute little to system inertia, resulting in faster system dynamics and reduced ability to withstand disturbances. Consequently, the system becomes more vulnerable to voltage instability, especially under sudden changes in load or generation.

Another critical issue in renewable-dominated systems is the emergence of weak grid conditions, often characterized by a low short-circuit ratio (SCR). High penetration of inverter-based resources reduces fault current levels, increasing the sensitivity of the system to disturbances and control interactions. Additionally, these resources provide limited reactive power support compared to conventional generators, which further aggravates voltage regulation problems during peak demand or contingency conditions. The combination of insufficient reactive power and increased loading can lead to progressive voltage decline and potential voltage collapse.

Moreover, the extensive use of power electronic converters in renewable integration introduces harmonic distortion into the system, degrading power quality and affecting voltage stability. Rapid variations in renewable output also result in voltage fluctuations and flicker, impacting sensitive loads and overall system performance. The situation becomes more complex with the simultaneous integration of dynamic loads such as electric vehicle charging stations (EVCS), which introduce additional uncertainty on the demand side.

Traditional voltage control mechanisms, such as on-load tap changers and capacitor banks, are often inadequate to handle these fast and nonlinear dynamics. Therefore, renewable-dominated power systems require advanced voltage stability assessment and control techniques, including real-time monitoring using voltage stability indices, intelligent optimization methods, and robust inverter control strategies. These approaches are essential

to ensure reliable, stable, and efficient operation of modern power systems under highly dynamic and uncertain conditions.

1.8 Integration of Renewable Energy for Voltage Stability Enhancement

The coordinated integration of solar PV and wind generation can significantly improve voltage profiles and reduce system losses. By placing these sources near load centres, reactive power support can be enhanced locally.

Benefits include:

- Improved voltage profile
- Reduced line losses
- Enhanced system reliability
- Increased hosting capacity of the network

1.9 Advanced Control Techniques for Grid Integration

With the increasing use of inverter-based systems, advanced control strategies are required to ensure stable and efficient operation, that offers:

- Fast dynamic response
- Accurate frequency estimation
- Harmonic rejection capability
- Robust performance under weak grid conditions

Such controllers play a crucial role in maintaining power quality and voltage stability.

1.10 Observation

- Modern power systems include high penetration of renewable energy sources, EV loads, and power electronic converters.
- These elements introduce variability, uncertainty, and nonlinear behavior into the system.
- As a result, voltage stability has become more complex and critical to maintain.
- Voltage stability depends on reactive power balance and system operating conditions.
- Disturbances or improper control can lead to voltage instability or collapse.

- Understanding voltage stability characteristics and influencing factors is essential.
- Advanced monitoring, control, and optimization techniques are required for reliable and secure system operation.

1.11 Motivation

The motivation for this research arises from the increasing operational stress on modern power systems due to high penetration of renewable energy sources and electric vehicle charging infrastructure. Recent voltage instability events and large-scale blackouts in India have demonstrated that conventional grid planning and control techniques are insufficient to handle rapid load variations, intermittent generation, and weak grid conditions. Uncoordinated deployment of EV charging stations leads to excessive voltage deviations, increased losses, and reduced voltage stability margins in distribution networks. At the same time, inverter-dominated renewable generation reduces system inertia and challenges traditional voltage and frequency control mechanisms. These concerns necessitate advanced planning methodologies and robust control strategies to ensure secure, reliable, and high-quality power supply in future grids.

- Recent major Indian blackouts (2012 National Grid, regional collapses) highlight the critical need for enhanced voltage stability assessment and mitigation frameworks.
- India is rapidly transitioning toward electric mobility and renewable energy, driven by national missions such as FAME, National EV Policy, and 500 GW renewable targets by 2030 and net zero by 2050.
- The large-scale deployment of EV Charging Stations (EVCS) introduces highly variable, impulsive, and location-sensitive loads, which severely impact voltage stability and feeder loading.
- Simultaneously, high penetration of solar and wind generation introduces intermittency, reverse power flows, and reactive power uncertainty, weakening traditional distribution system operation.
- Conventional voltage control using OLTCs, capacitor banks, and fixed compensators is too slow and insufficient for fast EVCS and renewable dynamics.

Motivated by these challenges, this research focuses on voltage stability investigations in modern power systems, with emphasis on:

- Optimal placement of EV charging stations using a novel hybrid optimization approach,
- Optimal allocation of solar PV and wind generation to enhance voltage stability and reduce losses, and
- Development of an advanced control strategy for grid-connected PV systems to ensure voltage regulation and power quality improvement at the Point of Common Coupling (PCC).

The proposed methodologies are validated using standard IEEE 33-bus and 69-bus distribution systems, along with detailed simulations in MATLAB/Simulink.

The outcomes of this research aim to provide practical insights and effective tools for system planners, utilities, and policymakers to enhance voltage stability, increase renewable hosting capacity, and enable reliable large-scale integration of EVCS and RES in future power networks.

1.12 Rationale of Research

- Optimal placement of EVCS is essential to prevent localized voltage collapse, thermal overloading, and high losses in urban and semi-urban feeders.
- Simultaneous optimal allocation of PV and wind provides localized voltage support and active-loss minimization, improving grid resiliency.
- With increasing inverter dominance, Grid-Following (GFL) inverters with Frequency Lock Loop (FLL) synchronization provide, fast voltage tracking, stabilize PCC voltage, enhance power quality, robust operation under weak grid and nonlinear (EV) loading conditions.
- This coordinated methodology directly supports, distribution system operators (DISCOMs), EV infrastructure planners and renewable energy developers.
- The research uses simulations in MATLAB/simpower system to assess the strategies performance under different operating scenarios.
- IEEE-33 bus distribution system is considered for validation of proposed research work.

1.13 Organization of the Thesis

This thesis is arranged into six comprehensive chapters structured with relevant sections, subsections, references, appendices, patent publication and a list of research publications. Here's a structured thesis outline presented below:

Chapter 1- This chapter presents the overall research background and motivation, highlighting the emerging challenges in maintaining voltage stability in modern power systems due to high penetration of electric vehicle charging stations (EVCS) and renewable energy sources (RES). This chapter clearly defines the research problem, objectives, scope, and significance of the study. It also outlines the methodological approach adopted and summarizes the key contributions of the thesis.

Chapter 2- Provides a comprehensive review of existing literature related to voltage stability analysis in distribution networks, the impact of EVCS integration, optimal placement of renewable energy sources, and recent advancements in optimization algorithms. It also reviews inverter control and synchronization techniques for grid-connected renewable systems. Based on the literature survey, critical research gaps are identified, which form the basis for the proposed work.

Chapter 3- This chapter presents the modeling of EVCS loads in the distribution system, including and voltage stability indices, along with the mathematical formulation of the optimization problem. It introduces the proposed hybrid Coati-Pelican Optimization Algorithm (COA-POA) and its implementation for optimal EVCS placement in the IEEE 33-bus distribution system. The effectiveness of the method is validated through simulations, evaluating voltage deviation, stability indices, and power loss reduction.

Chapter 4- This chapter presents the optimal allocation of photovoltaic and wind generation units using the World Cup Optimization (WCO) technique. The coordinated impact of EVCS, PV, and wind integration on voltage profile, system losses, and stability indices is analyzed and validated on standard IEEE 33 & 69 bus distribution test systems.

Chapter 5- This chapter is dedicated to the design and validation of a Complex Band-Pass Filter-based Frequency Locked Loop (CBF-FLL) controller for a grid-connected photovoltaic system. The controller's performance is assessed under varying irradiance

levels, dynamic load conditions, non-linear loads, and weak grid scenarios, with emphasis on voltage regulation and power quality enhancement.

Chapter 6- This chapter concludes the thesis by summarizing the major findings and contributions of the research work. It also discusses the practical implications of the proposed methodologies and outlines potential directions for future research.

CHAPTER -2 LITERATURE SURVEY

This chapter presents a comprehensive review of existing research related to the optimal placement of Electric Vehicle Charging Stations (EVCS), distributed generation (DG), and advanced control strategies for modern power systems. It focuses on significant contributions from previous studies addressing voltage stability enhancement, power loss minimization, and efficient integration of renewable energy resources within distribution networks.

A detailed examination of various Voltage Stability Indices (VSIs), optimization techniques, and hybrid algorithms employed for optimal siting of EVCS and DG units is provided. In addition, the chapter reviews recent developments in advanced inverter control strategies, particularly those aimed at improving grid synchronization, voltage regulation, and power quality under dynamic and weak grid conditions.

Furthermore, the chapter highlights the current research trends and technological advancements in the coordinated integration of EVCS and renewable energy sources, along with the role of intelligent and adaptive control methods. Based on this review, the existing research gaps including limitations in voltage stability consideration, multi-objective optimization, and robust controller design are clearly identified.

These gaps form the foundation for defining the objectives of the present research work, and guide the selection of suitable optimization techniques and control strategies for enhancing voltage stability and overall system performance in modern distribution networks.

2.1 Review on Voltage Stability Indices in Renewable-Rich Systems

Recent definitions of power system stability, including voltage stability definition based on the integration of renewable energy resources into the grid through HVDC convertors, have been proposed by the IEEE/CIGRE task group [1]-[2]. The continuity of proper power flow in the interconnected electrical power systems is maintained by designing the system carefully without any restraint. In earlier beings, voltage instability has been the key reason of several major blackouts in the world in significant part of power systems. In [3]-[13] from

1965 to 2015, many power outages have been pointed out and demonstrating that the voltage variability issues obligated a significant incident in many of the cases. The voltage breakdown term is additionally utilized rather than voltage instability and this is the interaction by which the arrangement of occasions going with voltage insecurity prompts a strangely low voltages or power outage in a huge portion of the power system network [3].

The capacity of a power system to maintain constant voltages at all its buses after being subjected to a disturbance from a specific initial operating condition is the IEEE definition of voltage stability [4]-[8]. The failure of reactive power sources to provide enough reactive power or the failure of power system cables to transmit the required reactive power can both cause voltage instability [9]. The reactive power is generally provided by generators excitation system and reactive power compensators such as shunt capacitors and other compensating devices. The leading instances producing voltage instability issues in the electrical power system network are gradual or sudden increase in the loading condition, maloperation of protective devices, sudden tripping of large rating power system apparatus like generators, transmission lines and power transformers, surpassing some generator units' reactive power limits and issues with on-load tap shifting transformers. Several solutions for the reduction of voltage instability in the power system are already exists. The most important one is as below [10].

1. Improving faulty buses and lines during the power system expansion phase (by DG units or other voltage-supporting apparatus)
2. Shunt capacitor device switching,
3. Load shedding,
4. FACTS device implementation to extend the voltage stability (VS) margin
5. The blocking of tap changer

Here the shedding of load is the latter line of shield. Another use of VSI's is producing the countermeasures in contradiction of voltage instability [11]-[16].

In these instances, the indices which have been used in real-time application, the data needed is provided by the PMU's who is the measure of wide area measurement system. To measure the voltage instability, a number of indices have been described in the studies [17]-[20]. Only the voltage and current of the buses are required, and very few indices depend on the impedance of the power system. Practically it is impossible to get power system impedance with high accuracy due to the atmospheric effects and deficiency in information. Thus, the performance of indices is most of the time associated with error as they are dependent on

power system impedance.

This chapter shows the review on various voltage stability indices considering several features and aspects such as method of voltage instability calculation, concept of voltage stability, equations and stability condition. For a variety of applications, including the positioning and capacity findings of DGs, the static and dynamic VS assessment, the ranking of buses and transmission lines contributing to voltage instability issues, and more, the analysis of the review results can be used to understand the upcoming works in voltage stability analysis and to select the best VSI, and the activation of countermeasures for controlling the system prior to voltage collapse.

2.1.1 Voltage Stability Index Need for Renewable Energy Integration

The trend towards renewable energy integration into the grid is increases and hence following challenges are brought into notice for large renewable energy integration in to the existing grid.

- Rises the ambiguity in the power flow and voltage profile of the system,
- It may lead to clashes of voltage and var control devices between interconnected power systems of unlike regions,
- Intensify the needless operation of discrete Var and voltage control devices,
- Decreases the system voltage stability and
- It constructs difficulties in the reactive power market

Also, distribution generators which are of small power generators (typically from 2 kW to 10 MW range) are integrating to grid to improve conventional electrical power system [21]-[22]. These technologies include wind and solar energy, microturbines, small hydro-power, small gas turbines, fuel cells, biomass etc. When Distributed generators are integrated to power system network it will benefit existing network by increasing voltage profiles and load factors, by reducing losses, peak operating costs. It also improves system reliability and efficiency [23]. To accomplish benefits, a suitable sizing and placement of distributed generator must need to be selected. The location of generator units has been selected according to voltage stability index. For the sitting and sizing of distributed generation nearly all the indices which has been able to regulate the weak transmission lines and buses can be used by using appropriate and accurate voltage stability index, better locations for the distributed generator units can be attained. Furthermore, complex index increases the computational time of the problem to be optimize especially in large power systems.

Therefore, the best solution for DG sitting and sizing issues is to employ an accurate and simple index. The voltage stability indices are categorized conferring to their forms (e.g., line, bus, and overall voltage stability indices), concepts used, equations, and stability condition in order to give a broad perspective for the proper selection of voltage stability indices. The accuracy of these assumptions is then evaluated in the following sections.

Voltage stability has become more crucial in modern distribution system owing to rising demands and the penetration of DG. Compared to traditional power systems, the ability of renewable energy producing systems to control voltage is constrained [24]-[26]. As inverter-based renewable energy generation systems replace traditional synchronous generators, the stability, frequency, and voltage of the power system are being put to the test [25]. When a power system's ability to control voltage falls below threshold, system behavior deteriorates. For instance, in a double-fed induction generator-based wind energy conversion system (DFIG-WECS), the capacity to modify voltage depends on the rate of wind generation penetration [26]. The classification procedure for voltage stability analysis in the system with renewable energy resources is shown in Figure 2.1.

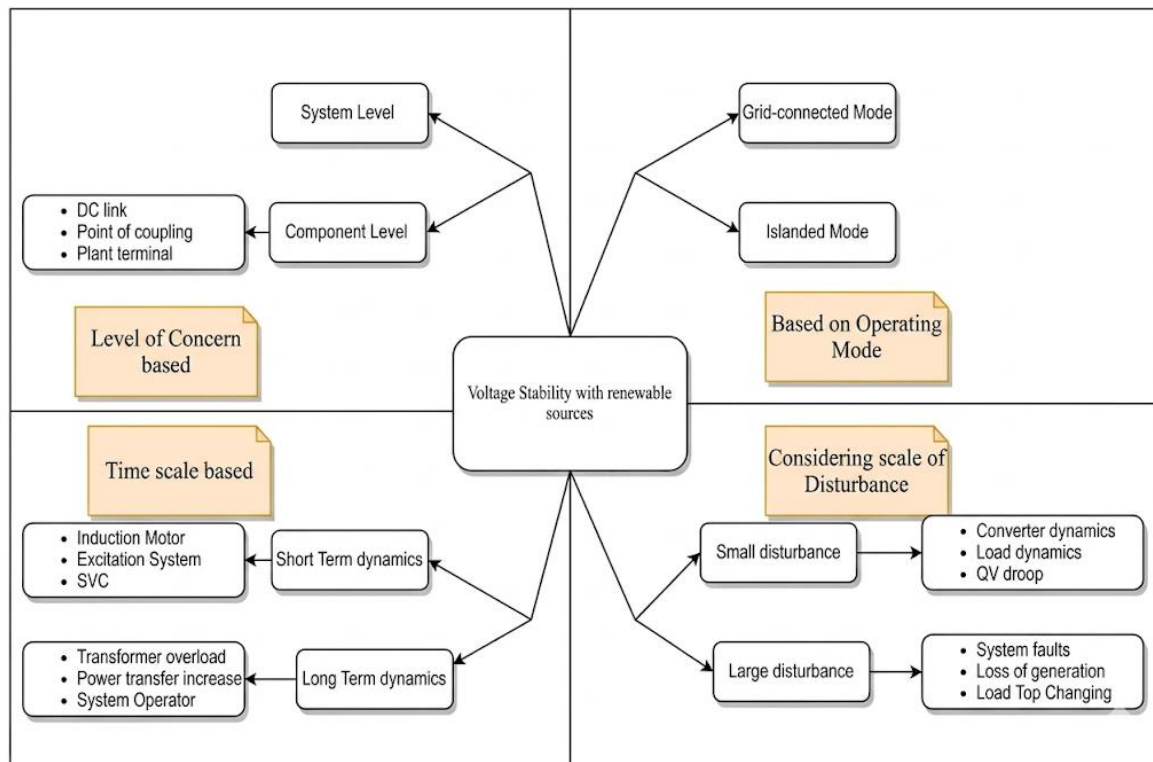


Figure 2. 1 Voltage stability comparison with renewable dominated power system

Analysis and verification have been done in several literature [27]-[47] for voltage stability analysis considering different case studies such as with only PV generation, only wind

generation, with hybrid distributed generator. Table 2.1 provides a brief overview of various operating modes with different generation sources and their corresponding verification platforms.

Table 2. 1 Overview of several ways of operation with varied generation

Generator type	References	Ways of operation
Wind generator	[27]-[31]	Integrated to grid
Photo Voltaic (PV)	[32]-[36]	
Wind and PV	[37]-[41]	
Hydro and PV	[42]	
Wind, PV and hydro	[43]	
Wind	[44]	Standalone or islanded
PV	[45]	
Wind and PV	[46] [47]	

2.1.2 Voltage Collapse Point Detection

Numerous VSI's have been reported in different literature. These VSIs has been classified as follows: [48]-[59]:

- based on singularity of Jacobian matrix
- system variables-based voltage stability indices
- Bus index, line index and overall voltage stability indices

The VSI's based on singularity of Jacobian matrix is mainly used to compute the voltage collapse point and to spot the voltage stability margin. Generally, two bus representation is used by most of the researchers to describe the voltage collapse criterion shown in Figure 2.2. The fundamental drawback of this approach is the high computing time required for bigger systems, where even minor topologic changes result in changes to the Jacobian matrix and necessitate repeated calculations of the matrix. They are not appropriate for determining the voltage stability in real time.

Moreover, use of indices based on singularity of Jacobian matrix concept can cause a rise in the running time of distributed generation sizing and sitting problems. In contrast, the various indices depend on system variables requires little computation time and are appropriate for real-time applications. The limitation of these indices is that it just shows the critical lines and busses of the system and cannot accurately estimate the stability margin. In many applications voltage stability indices are used to spot the weak buses and weak lines in power

system or energizing the countermeasures in contradiction of voltage instability. Consequently, it is very essential to classify the various voltage stability index which have been described in this study and can be very useful to the researchers who will going to work on voltage stability.

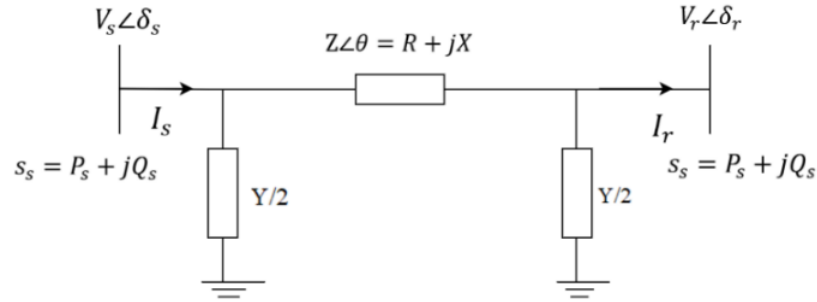


Figure 2. 2 Two bus power system representation

Table 2.2 presents various voltage stability indices based on the Jacobian matrix that have been reported in the literature. The table summarizes the corresponding references, mathematical expressions, underlying concepts used for stability assessment, and the associated stability conditions for each index. These indices are widely utilized to evaluate the voltage stability performance and identify weak buses in power systems under different operating conditions.

Table 2. 2 Voltage stability indices based on Jacobian Matrix

Index	Refere nce	Expression	Concept Used	Stability Condition
$Det J$ $Det J_R$	[60]	$ J = \begin{vmatrix} \frac{\partial P}{\partial V} & \frac{\partial P}{\partial \theta} \\ \frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial \theta} \end{vmatrix}$ $ J_R = J_{QV} - J_{QS} * J_{PS}^{-1} * J_{PV} $	Power flow	$ J \neq 0$ $ J_R \neq 0$
Singular/ Eigen values/Mod al analysis	[61]- [62]	Minimum Value	Eigen/singular power flow	All Eigen singular Value should be positive

$J^C \in C^{2n \times 2n}$	[63]	$J^C = \begin{bmatrix} -I^n & V^n - Y^b \\ -V^n Y^b & I^n \end{bmatrix}$ $\wedge = (V^n)^{-1} Y^n V^n$	Jacobian singularity	$\lambda^{cr} = \min_{\lambda_i} \lambda_i - 1 = 0$
Sensitivity Factors	[64]	$VSF_1 = \max_1 \left\{ \frac{dV_1}{dQ_1} \right\}$	Singularity of Jacobian	VSF_1 should be small positive
Inverse sensitivity factors (VQ-sensitivities)	[65]	$IVSF = 1/VSF$	Inverse of reduced Jacobian J_R^{-1}	$IVSF \neq 0$
Second order index	[66]	$C = \frac{\sigma_{\max}}{c_o \left(\frac{d\sigma_{\max}}{d\lambda_{total}} \right)}$	Singularity of Jacobian	$C > 0$
P and Q angle	[67]	$\alpha_1 = \cos^{-1} \left\{ \frac{(\nabla f_1 \cdot Tag_1)}{(\ \nabla f_1\ \ \text{Tag}_1\)} \right\}$	Singularity of Jacobian	$\alpha_1 < 90^\circ$
Tangent Vector Index	[68]	$TVI_1 = \left \frac{dV_1}{d\lambda} \right ^{-1}$	Inverse sensitivity factors	$TVI_1 \leq \epsilon$
Test function	[69]	$t_{cc} = e_c^T J J_{cc}^{-1} e_c $	Singularity of J	$t_{cc} \neq 0$
$S\lambda\omega$	[41]	$S\lambda\omega = \frac{\Delta\lambda}{\Delta\omega} = - \frac{MF _{\omega}}{MF _{\lambda}}$ $\Delta\lambda_i = \sum_r S_{ir0} \Delta\omega_r$	Jacobian matrix singular point	Loading margin measures by formulation

2.2 Comparison of VSI/Classification

Figure 2.3 presents the classification of voltage stability analysis techniques used for assessing the stability and security of modern power systems. Various conditions for developed VSI's are as follows:

- Power flow using Jacobian singularity
- P-V and V-Q curves
- Based on Theorem of maximum power transfer

- Based on power transfer limit of transmission line
- Lyapunov stability theory

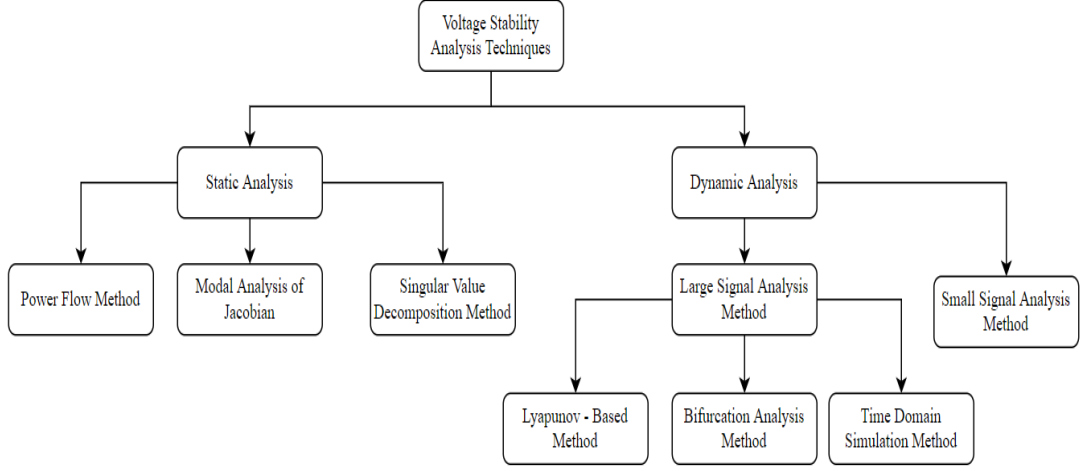


Figure 2. 3 Classification of voltage stability methods

2.2.1. Load Flow using Jacobian Singularity

In load flow, the steady state limit is directly associated to Jacobian matrix. The voltage instability state can be indicated by the singularity of Jacobian matrix after load flow and as a result, the eigen values of the linearized system matrix may serve as a warning sign of impending voltage collapse. At different buses, the real and reactive power equations can be expressed by non-linear equations as in equation shown in (2.1) and (2.2).

$$\Delta P_i = P_{i,sp} - |V_i| \sum_{j=1}^n |V_j| [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin((\theta_i - \theta_j))] \quad (2.1)$$

$$\Delta Q_i = Q_{i,sp} - |V_i| \sum_{j=1}^n |V_j| [G_{ij} \sin(\theta_i - \theta_j) + B_{ij} \cos((\theta_i - \theta_j))] \quad (2.2)$$

By using Taylor's series expansion to linearize the equation above the power balance equations and ignoring higher order terms yields (2.3).

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial V} & \frac{\partial P}{\partial \theta} \\ \frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial \theta} \end{bmatrix} \begin{bmatrix} \Delta V \\ \Delta \theta \end{bmatrix} \text{ or } \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] \begin{bmatrix} \Delta V \\ \Delta \theta \end{bmatrix} \quad (2.3)$$

Where:

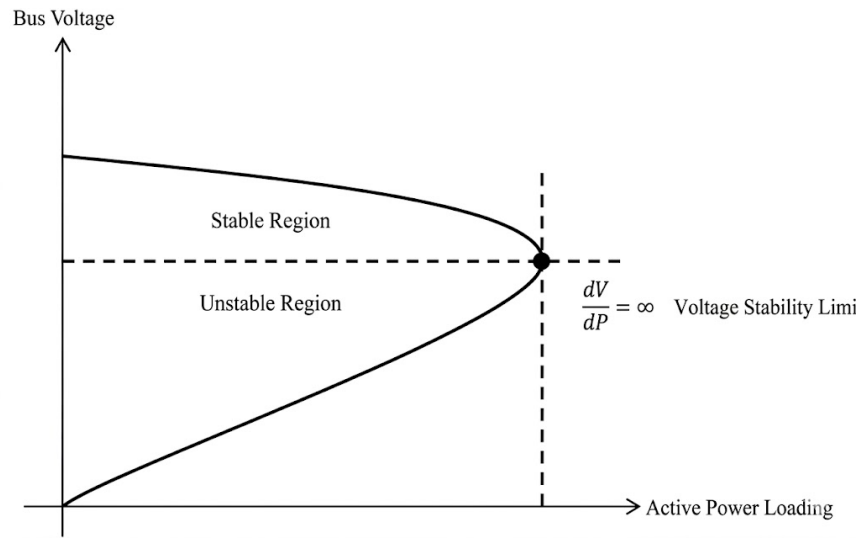
ΔP , ΔQ : change in active and reactive powers respectively

ΔV , $\Delta \theta$: change in voltage and load angle respectively

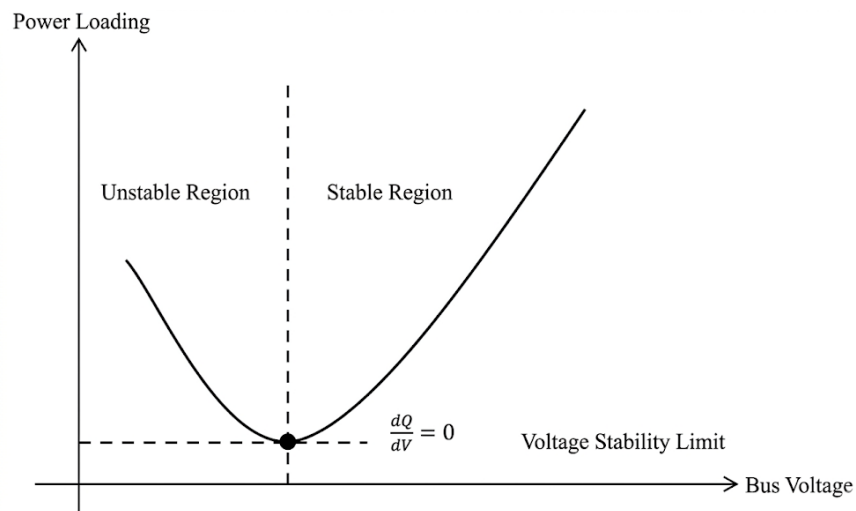
J: Jacobian matrix

2.2.2 P-V and Q-V Curves Load Margin [55]-[57]

The fundamental and conventional method of observing voltage to proximity of collapse, the P-V curve and Q-V curve is shown in Figure 2.4 (a) and (b) respectively, which displays the stability regions. The amount of additional load required to cause voltage collapse under specific load-increasing assumptions is known as the loading margin at a specific operational condition. It has been heavily utilized in voltage stability research to evaluate other indices' performance. In reality, the loading margin is determined using the direct and continuous power flow methods.



(a)



(b)

Figure 2. 4 (a) P-V curve (b) Q-V curve

2.2.3 Maximum Power Transfer Theorem

This method is the most practical for stability analysis and real-time regulation of power systems since it makes determining system equivalents simple. Thevenin's theory had been applied to obtain the network equivalent in the vast majority of cases. A simple technique for estimating the global voltage stability of a complex power network involves using the system equivalent at a specific bus, as shown in Figure 2.5.

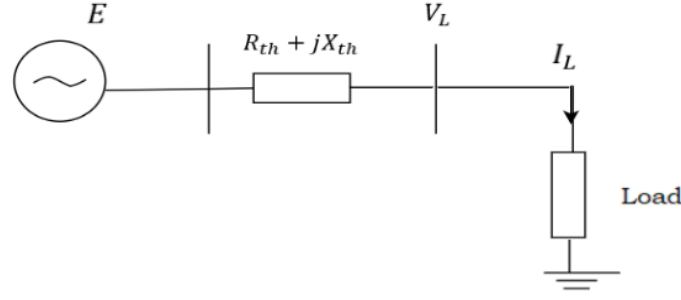


Figure 2. 5 Thevenin's equivalent circuit

2.2.4 Power Transferable Limit of a Transmission Line

Majority of the line indices were discovered by studying the capability of power transfer through a transmission line. When there is no practical way to lower the voltage at the receiving end, the maximum power limit is reached.

Two bus transmission line model is shown in Figure 2.6. By condensing the formulas for receiving end active and reactive powers, the receiving end voltage of the line in Figure 2.6 can be calculated using the following calculation.

$$V_r^4 + (2P_r R + 2Q_r X - V_s^2)V_r^2 + (P_r^2 + Q_r^2)Z^2 = 0 \quad (2.4)$$

As a result, the standard for determining the critical limits of various line VSIs is to equalize the expression for the discriminant in equation (2.4) to zero.

Where:

$V_s \angle \delta_s$ & $V_r \angle \delta_r$: Sending and receiving end bus voltages

$(P_s + jQ_s)$ & $(P_r + jQ_r)$: Sending and receiving end real and reactive powers

R, X, Y : Resistance, inductive reactance and shunt half line charging admittance of transmission line respectively.

Few indices in terms of transmission line parameters i.e ABCD parameters have also been derived by using the pie-model of transmission line as shown in the Figure 2.7.

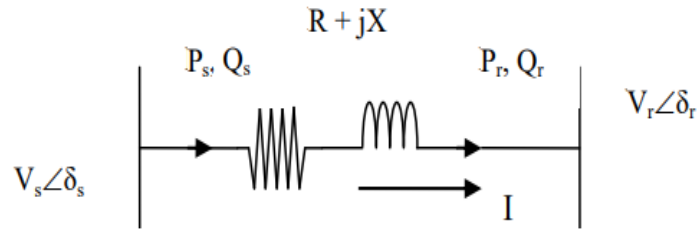


Figure 2. 6 Two bus transmission line model

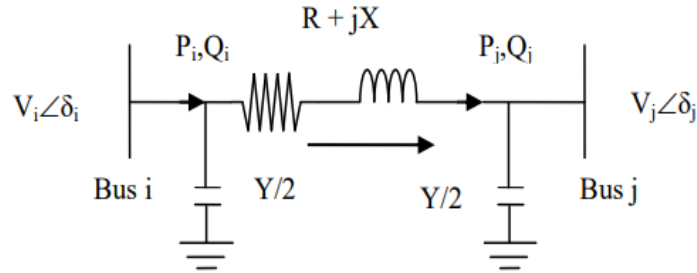


Figure 2. 7 Line model with shunt admittance

2.2.5 Lyapunov Based Stability Theory

This theory had been originally identified for direct stability studies of power systems. Therefore, the method based on it had been efficiently applied and employed as a VS predictor in [58-59]. The classification criterion for recognize the voltage collapse has been shown in Figure 2.8.

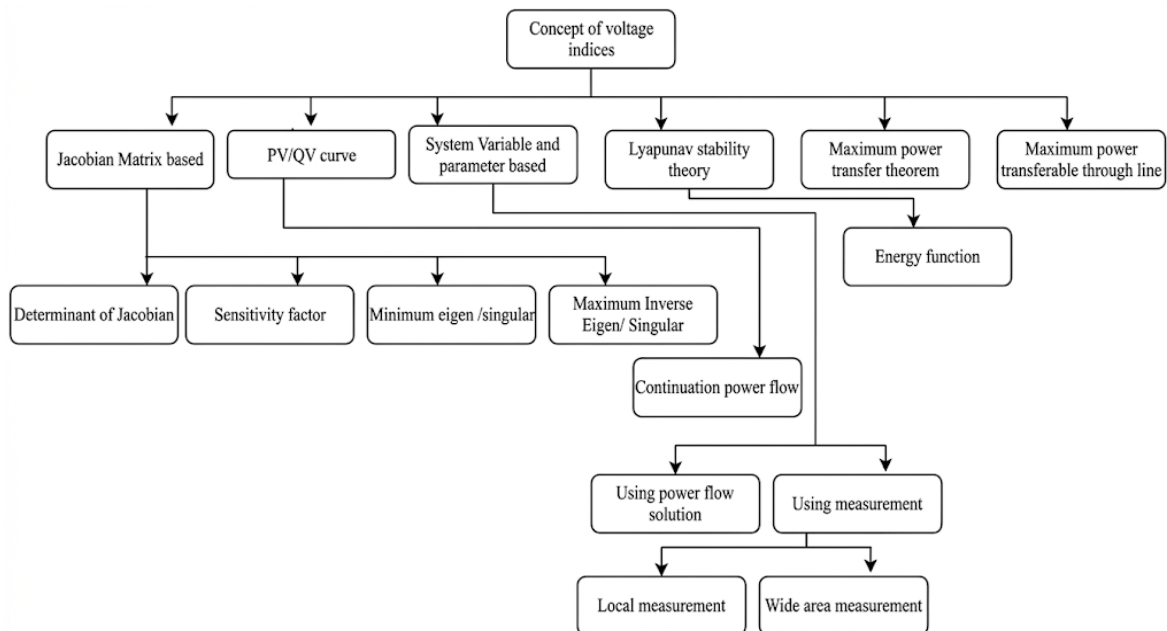


Figure 2. 8 Voltage Collapse recognition criterion

Both load flow solutions and measurements of the voltages, powers, and currents pumped into several buses can be used to determine power system variables. The power system's weak points are identified by an index derived from these system variables and characteristics, which is used to launch remedial action against voltage collapses. As a result, these are categorized as follows based on the identification of the part susceptible to voltage collapses: 1. Line Indices 2. Bus Indices 3. Overall Indices.

The buses that are closest to the voltage stability limits can be found using bus indicators, making them prime candidates for installing shunt FACT's controllers. Similar to this, series connection in weak lines has been achieved using line indices. The overall indices don't just flag poor buses or lines; they also predict the stability level of the entire power system. The results of an extensive survey are presented in this section, where the imperative indices that have been created up to now are stated in sequential order along with the criteria that directed their development.

- **Line VSIs:** These indices are referred to a transmission line which can be used to assess voltage stability. The two-bus representation of a system in Figure 2.1 provides the foundation for all line indices used for voltage stability analysis. Because of this, most line indices have the same theoretical foundation; the assumptions made by each index may vary. Table 2.3 displays the line indices used for voltage stability analysis that have been proposed in the literature.
- **Bus VSI's:** Assess the voltage stability of system buses only but do not give any details regarding weak facilities that could experience voltage related issues in the system. Thus, it is not possible to identify deficient facilities using bus voltage stability indices. This section examines the bus index. Table 2.4 displays the bus voltage stability indices that have been suggested in the literature.
- **Overall VSI's:** The system buses and lines have no bearing on these types of indicators. As a result, the total voltage stability indices can only be used to predict when a system will collapse. They cannot identify weak buses or weak lines. Table 2.5 lists a few overall voltage stability indices that have been suggested in the literature.

Table 2. 3 Line voltage stability indices

Index	Refere nce	Expression	Concept Used	Stability Condition
Line Stability Factor	[71]	$LQP = 4 \left(\frac{X}{V_s^2} \right) \left(Q_r + \frac{P_s^2 X}{V_s^2} \right)$	Line Power transfer capability (LPTC)	$LQP < 1$
Voltage Stability Load Index	[72]	$VLSI = \frac{4[V_s V_r \cos \delta - V_s^2 \cos \delta]}{V_s^2}$	LPTC	$VLSI < 1$
Transmission Path Stability Index	[73]	$TPSI = 0.5V_g - \Delta V_d$	Maximum power transfer theorem	$TPSI > 0$
Line Stability Index	[74]	$L_{mn} = \frac{4XQ_j}{[V_i \sin(\theta - \delta)]^2}$	LPTC	$L_{mn} < 1$
Line Stability Index	[75]	$L_p = \frac{4RP_j}{[V_i \cos(\theta - \delta)]^2}$	LPTC	$L_p < 1$
Fast Voltage Stability Index	[76]	$FVSI = \frac{4ZQ_j}{V_i^2 X}$	LPTC	$FVSI < 1$
L_{sr} Index	[77]	$L_{sr} = \frac{S_r}{S_{r(\max)}}$	LPTC	$L_{sr} < 1$
Voltage Load stability Bus Index	[78]	$VLSBI = \frac{V_r}{\Delta V}$	LPTC	$VLSBI > 1$
Voltage Stability Margin Index	[79]	$VSMI = \frac{\delta_{\max} - \delta}{\delta_{\max}}$	Maximum power transferable through a transmissio	$VSMI > 0$

			n line [MPTTTTL]	
Power Transfer Stability Index	[80]	$PTSI = \frac{2S_r(1 + \cos(\theta - \delta))}{V_s^2}$	[MPTTTTL]	$PTSI < 1$
Novel Line Stability Index	[81]	$NLSI = \frac{P_r R + Q_r X}{\frac{V_s^2}{4}}$	[MPTTTTL]	$NLSI < 1$
Line Stability Index	[82]	$L_{ij} = \frac{4Z^2 Q_r X}{V_s^2 (R \sin \delta - X \cos \delta)^2}$	[MPTTTTL]	$L_{ij} < 1$
Line collapse Proximity Index	[83]	$LCPI = \frac{4A \cos \alpha (P_j B \cos \beta + Q_j B \sin \beta) \text{Voltage}}{(V_i \cos \delta)^2}$	quadratic equation solution	$LCPI < 1$
Novel Voltage stability Index	[84]	$NVSI = \frac{2ZX \sqrt{P_r^2 + Q_r^2}}{2Q_s X - V_s^2}$	[MPTTTTL]	$NVSI < 1$
Modified voltage stability indices	[85]	$MVSI_j = \frac{4(Q_j Y_{jj} \sin \varepsilon_{jj})}{\left(\sum_{i=1, i \neq j}^N V_i Y_{ij}\right)^2}$	Active and reactive power transfers	$MVSI < 1$
Smoothering Reactive Power Loss based Voltage Instability Detection Index	[86]	$QLVIDI_{(t)} = \frac{CQL_{(t)}}{CQLB_{(t)}} - \frac{CQL_{(t-\tau)}}{CQLB_{(t-\tau)}}$	PMU	Details are in reference
Real-time short-term	[87]	Details are in reference	PMU	data collection

voltage stability (STVS) assessment				Inaccuracy (Z)
Real time VSI	[108]	$VSI = \min \left(\frac{P_{\max} - P}{P_{\max}}, \frac{Q_{\max} - Q}{Q_{\max}}, \frac{S_{\max} - S}{S_{\max}} \right)$ $P_{\max} = \frac{QR}{X} - \frac{V_s^2 R}{2X^2} + \frac{ Z_{th} V_s \sqrt{V_s^2 - 4QX}}{2X^2}$ $Q_{\max} = \frac{PX}{R} - \frac{V_s^2 X}{2R^2} + \frac{ Z_{th} V_s \sqrt{V_s^2 - 4PR}}{2R^2}$ $S_{\max} = \frac{V_s^2 \left[Z_{th} - (\sin(\theta)X + \cos(\theta)R) \right]}{2(\cos(\theta)X - \sin(\theta)R)^2}$	PMU	System is unstable if the VSI is 0 and 1 when stable.

Table 2. 4 Bus voltage stability indices

Index	Referen ce	Expression	Concept Used	Stability Condition
L-Index	[88]	$L_j = \left 1 - \sum_{i \in \alpha_g} \frac{F_{ji} V_i}{V_j} \right $	quadratic voltage equation	$L_j < 1$
Voltage Index Predictor	[89]	$\Delta S = \frac{(V_j - Z_{th} I_{ij})^2}{4Z_{th}}$	MPT	$\Delta S > 0$
P-Q Boundary	[90]	$P_{cr} = -\frac{E^2 R_{th}}{2X_{th}^2} + \frac{ Z_{th} E}{2X_{th}^2}$ $Q_{cr} = \frac{P_L X_{th}}{R_{th}} - \frac{E^2}{2R_{th}^2} + \frac{ Z_{th} E \sqrt{E^2 - 4P_L R_{th}}}{2R_{th}^2}$	Feasible solution of voltage equation s	$P_L < P_{cr}$ $Q_L < Q_{cr}$
Voltage Collapse Prediction Index	[91]	$VCPI_k = \left 1 - \sum_{m=1, m \neq k}^n \frac{V'_m}{V_k} \right $	Feasible solution of power flow and voltage	$VCPI_k < 1$

			equation s	
S Difference Criterion	[92]	$SDC = \left 1 + \frac{\Delta V_r I_r^*}{V_r I_r^*} \right $	rise in the line's reactive power losses	$SDC > 0$
Impedance Stability Index	[93]	$ISI = \frac{Z_L - Z_{th}}{Z_L}$	MPT	$ISI > 0$
$\frac{Z_L}{Z_S}$ ratio	[94]	$\frac{Z_L}{Z_S} = \frac{M+1}{-M \cos \beta + [(M \cos \beta)^2 M^2 + 1]}$ Where, $M = \frac{(S_2 - S_1)(Y_2 + Y_1)}{(S_2 + S_1)(Y_2 - Y_1)}$	MPT	$\frac{Z_L}{Z_S} > 1$
Voltage Stability Index	[95]	$VSI_i = \left[1 + \left(\frac{I_i}{V_i} \right) \left(\frac{\Delta V_i}{\Delta I_i} \right) \right]^\alpha$	rise in the line's reactive power losses	$VSI_i > 0$
Equivalent Node Voltage Collapse Index	[96]	$ENVCI = 2E_k V_n \cos \theta_{kn} - E_k^2$	Voltage quadratic equation solution	$ENVCI > 0$
Linearized motor voltage stability Index	[97]	$LMVSI_i = \frac{MVSI_i}{\left d(MVSI_i) / d\lambda_i \right }$ where, $MVSI_i = \det(A_i) $	Equivalen t load state matrix singularit y with dynamic induction motor model	$LMVSI_i > 0$

DSY (derivative of the load apparent power with respect to its admittance)	[98]	$DSY = \frac{\Delta S_l}{V_l^2 \Delta Y_l}$	MPT	$DSY > 0$
Voltage stability Risk indices	[99]	$VSRI_i = \frac{1}{N} \left[\frac{\sum_{i=j-N+1}^j (d_i + d_{i-1}) \Delta t}{2} \right]$	Transient variation of the system voltages	negative index, highest risk of voltage instability
Simplified Voltage Stability Index	[48]	$SVSI_i = \frac{\Delta V_l}{\beta V_l}$	MPT	$SVSI_i < 1$
Linear M- index	[49]	$M_i = 1 - \frac{ \overline{V}_l \overline{E}_{effi} - \overline{V}_l }{ \overline{V}_{cri} ^2}$	Voltage quadratic equation solution	$M_i > 0$
dV/dQ index	[50]	$I_i \triangleq \sum_{k \in l} \frac{Q_j \delta V_i}{V_k \delta Q_k}, i \in l$		$I_i \rightarrow +\infty$ at VC
dV_L/dV_G index		$J_i \triangleq \sum_{k \in g} \frac{\delta V_i}{\delta V_k}, i \in l$	Singularity of Jacobian matrix	$J_i \rightarrow +\infty$ at VC
dQ_L/dQ_G index		$K_i \triangleq \sum_{k \in g} \frac{\delta Q_k}{\delta Q_j}, i \in l$		$K_i \rightarrow -\infty$ at VC
P - index	[51]	$P-index_j = \frac{-2 \frac{P_{Lj}}{V_j} \frac{dV_j}{dP_{Lj}}}{1 - 2 \frac{P_{Lj}}{V_j} \frac{dV_j}{dP_{Lj}}}$	Load flow Jacobian matrix	$P-index_j < 1$

Table 2. 5 Overall voltage stability indices

Index	Reference	Expression	Concept Used	Stability Condition
Voltage Instability Proximity Index	[52]	$VIPI = \cos^{-1} \left\{ \frac{y_s^T y(a)}{\ y_s\ \ y(a)\ } \right\}$	Feasible solution of Power flow equations	$VIPI > 0$
Sensitivity Matrix	[100]	$S_{Qgq} = -\phi_z^T (\phi_z^T)^{-1} \nabla_z Q_g$	at voltage collapse point Sensitivities turn out to be infinite	$S_{Qgq} > 0$ at VC It changes sign through infinity
Area of Voltage Stability Region	[101]	$AVSR = \int_{P_l}^{P_n} [Q(P) - Q_l] dP$	Possible solution of Power flow equations	$AVSR > 0$
Network sensitivity approach	[102]	$SG_p = \frac{P_{gt}}{P_{dt}}$ $SG_q = \frac{P_{gt}}{Q_{dt}}$	P-V curve	$SG_p \rightarrow \infty$ at VC $SG_q \rightarrow \infty$ at VC
Voltage Instability Monitoring Index	[103]	$VIMI_k = W_1(k) \frac{DFR_k}{DFR_{\max}} + W_2(k) \frac{CVD_k}{CVD_{\max}}$	Voltage Deviation and consecutive voltage deviation	$VIMI_k < 1$

2.3 Cyber-Physical and ML-Based VSI Methods

Power system stability challenges have recently been addressed using novel monitoring, control, and computation approaches like ML (machine learning) and cyber-physical systems. The authors of [104] utilized voltage stability indices (VSIs) along with machine learning techniques for real-time monitoring of long-term voltage stability in power systems.

The proposed approach demonstrated the capability of accurately predicting voltage stability conditions under varying operating scenarios. In [105], an intelligent collaborative balancing mechanism was presented for dependable cyber-physical network components to address instability issues and improve system performance and operational reliability. The method proposed in [106] employed a Kernel Extreme Learning Machine (KELM) approach for long-term voltage stability monitoring of power system areas using synchrophasor measurement data.

The authors of [107] provided a more effective approach for stating the ideal composition sites of PMUs, which uses a local index load impedance modulus margin (LIMM) index. The deep neural network (DNN) is also used to determine the nonlinear relationship between the operational status of the power system and its corresponding LIMM. As a result, using the state variables for the buses provided by the installed PMUs, the value of the appropriate LIMM may be anticipated. In order to help the system operator, assess the operating environment and take appropriate action, the offered technique increases the LIMM's computation speed and provides real-time estimations of the system voltage stability level. Synchrophasor-based real-time voltage stability index estimation for monitoring power system stability conditions was discussed in [108]. The proposed method facilitates faster evaluation of voltage stability levels and assists system operators in taking preventive control actions under critical operating conditions

2.4 Literature Review on Optimal EVCS Placement

The demand for electricity is increasing due to rapid urbanization, industrialization, and population growth. Renewable Energy Sources (RES) play a crucial role in meeting this growing demand for electrical energy. In addition, a sharp rise in RES electricity generation is anticipated to meet demand in the near future [109]. To enable the industry's sustainable expansion, an infrastructure for electric vehicle charging stations (EVCS) must be developed. Higher voltage variation and power losses in the electrical distribution system may arise from the unplanned placement of EVCS. Modern power networks face a significant problem with voltage instability since there isn't enough generation and transmission capacity to meet growing demand, as EV charging is associated as load on the system. In addition to it, the numerous technical and financial apprehensions are posed to the distribution network. Therefore, it is imperative to install EVCSs at optimal locations in order to reduce the effect of EV charging load on the distribution network. Hence, there is

an urgent need for continuous monitoring and regulation of power systems based on the Voltage Stability Index (VSI).

The advancement of battery technology has made it possible for electric vehicles (EVs) to overcome the drawbacks of the conventional transportation system. The demand for electric vehicles varies based on driving habits and distance travelled. The distribution network powers charging stations, which provide electricity to EVs [110]. Since the EV is regarded as a single-phase load, line overloading may result by connecting it to any phase of a three-phase line [111]. RES is added to meet the growing demand for power in EV charging stations. Voltage instabilities are being caused by the growing use of renewable energy sources (RES) in distribution networks and microgrids because of their inherent uncertainties.

Moreover, Deep learning-based approaches for short-term voltage stability assessment of power systems were presented in [112], highlighting the effectiveness of intelligent techniques for fast and accurate stability prediction. A comprehensive review on the application and control of Flexible AC Transmission System (FACTS) devices for voltage stability enhancement in renewable-integrated power grids was discussed in [113]. Optimal power flow considering the integration of FACTS devices and stochastic wind power generation using the Krill Herd optimization algorithm was investigated in [114]. A detailed review on hybrid optimization techniques for the optimal placement of distributed generation in distribution networks was presented in [115]. The optimal location of electric vehicle charging stations and their impacts on power distribution networks, including voltage profile and power loss, were analyzed in [116]. Reactive power capability and operability of distributed energy resources for improving voltage stability in distribution networks were discussed in [117].

Several voltage stability assessment techniques have been proposed in the literature to improve the monitoring and secure operation of modern power systems. A new line voltage stability index for accurate voltage stability assessment and comparative performance evaluation with existing indices was introduced in [118], demonstrating improved sensitivity in identifying weak buses and critical operating conditions. A generalized voltage stability index applicable to different power system configurations was presented in [119], offering a reliable framework for voltage stability assessment under varying loading conditions. A modern voltage stability index for predicting voltage collapse and estimating maximum

loadability while identifying weak buses and critical transmission lines was proposed in [120], showing enhanced prediction capability for stressed systems.

A comprehensive review of voltage stability indices developed over the past three decades was provided in [121], highlighting their evolution, mathematical formulations, and practical significance in power system stability studies. The optimal placement of FACTS devices integrated with electric vehicle charging stations using Particle Swarm Optimization for improving voltage stability and system performance was investigated in [122]. A detailed comparison and review of various voltage stability indices, including their advantages, limitations, and practical applications, was presented in [123]. Furthermore, voltage stability assessment using line voltage stability index for effective detection of weak buses and critical lines in power systems was discussed in [124], emphasizing its computational simplicity and effectiveness for real-time stability monitoring. Together, these studies demonstrate the importance of voltage stability indices as efficient tools for ensuring secure and reliable operation of modern power systems.

Optimal Power Flow (OPF) is widely used to determine the optimal operating state of power systems by achieving a balance between system security and economic operation. The primary objective of OPF is to optimize control variables while satisfying system operating constraints [125]. In [126], an OPF framework incorporating voltage stability analysis was presented using the Salp Swarm Optimizer, where objectives such as power loss minimization and voltage profile improvement were effectively achieved. The optimal integration of distributed generators (DGs) in radial distribution systems considering the presence of plug-in electric vehicles (PEVs) was investigated in [127]. The study focused on minimizing active power losses and improving voltage profile under varying load conditions using bio-inspired optimization algorithms.

An optimal reactive power dispatch approach for real power loss minimization and voltage stability enhancement using the Artificial Bee Colony Algorithm was proposed in [128], considering both continuous and discrete control variables. Voltage stability improvement in distribution networks using soft open points was discussed in [129], demonstrating enhanced voltage regulation and operational flexibility. These optimization-based techniques are highly effective in identifying weak buses and determining optimal locations for DG placement and system support devices.

Extensive research has been carried out on voltage stability enhancement in distribution systems. However, the increasing penetration of renewable energy sources and electric vehicle charging stations (EVCS) has introduced additional operational complexities in distribution networks. Despite the growing importance of EV-integrated systems, only limited studies have focused specifically on voltage stability enhancement in EVCS-connected distribution networks.

The more relevant and recently available literature for voltage stability enhancement in EVCS-connected distribution networks is studied and findings from the same are listed here below for better understanding.

A multi-objective optimal power flow approach for improving static voltage stability margin was presented in [130]. The study focused on enhancing system voltage stability while simultaneously optimizing other operational objectives under different loading conditions. Voltage stability assessment and enhancement of power grids with increasing wind energy penetration were investigated in [131]. The study analyzed the impact of large-scale wind integration on system stability and proposed suitable enhancement techniques to improve voltage profile and secure grid operation under renewable energy penetration.

The Mayfly Optimization Algorithm was used by [132] to assess voltage stability in an IEEE 30-bus system that combines thermal and renewable energy sources. Fuzzy logic was utilized to maximize a number of objectives, and various situations were evaluated using the Preference Selection Index (PSI) and Line Stability Index (Lmn). The Lmn performed the worst, while PSI reduced reactive power. In order to reduce waiting time and expenses, [133] created a Dynamic System Voltage Stability (DSVS) index using a probabilistic model for EV charging loads. The Gram-Charlier expansion method and cumulants were used to validate the dynamic stochastic power flow. The linear weighted sum approach was used to merge several objectives into a single objective. The IEEE-33 bus power distribution system was used to validate the method, which demonstrated increased EV penetration and better system stability [134].

A unique method for the best placement and dimensions of plug-in electric vehicle charging stations within a connected transportation and electrical network is put forth by [135]. The paper discusses the difficulties brought on by growing PEV use, including line overloads, system losses, and voltage swings. In order to minimize the cost of constructing EVCSs as well as active power losses in the electrical grid, it formulates a multi-objective optimization problem. A comprehensive game-theoretic model for competition among electric vehicle

charging stations (EVCS) was presented in [136]. The study analyzed the strategic interactions between charging stations considering pricing, customer behavior, and market competition to improve the operational efficiency and profitability of EVCS networks. A multi-objective approach for voltage stability enhancement and power loss reduction in distribution systems was proposed in [137]. The study utilized network reconfiguration and distributed generation allocation under PQV and P bus conditions to improve voltage profile, minimize losses, and enhance overall system performance. Optimal allocation of PV-STATCOM for ancillary service provision in distribution systems was proposed in [138]. Advanced bio-inspired optimization techniques for solving engineering and optimization problems were developed in [139],[140]. A nature-inspired Pelican Optimization Algorithm and its application in microgrid energy management were discussed in [141], [142]. Optimal placement of distributed generators considering bus constraints was studied in [143]. Voltage stability assessment with wind and solar PV integration was presented in [144]. Mathematical modeling of electric vehicle performance under different driving cycles was investigated in [145]. Optimal allocation of hybrid renewable energy systems and distributed generation using advanced optimization techniques was discussed in [146], [147]. A novel Hybrid Chimp-Sine Cosine Algorithm for solar photovoltaic module parameter extraction was proposed in [148]. The study demonstrated improved accuracy and efficiency in estimating PV module parameters, which enhances the modeling and performance analysis of solar photovoltaic systems under varying operating conditions. Optimal sizing and smart charging capabilities of EV charging stations considering quality of service were analyzed in [149]. An optimal planning strategy for EV charging stations in coupled power and transportation networks was presented in [150]. The planning technique incorporates the transportation network by using the Floyd-Warshall algorithm to find the shortest travel routes for PEVs. In order to minimize DG investment costs and attain an ideal voltage profile, [151] concentrate on strategically placing DG units in a smart community. In [152], the best places for DG sources are found using Genetic Algorithm (GA) and PSO, with the goal of improving voltage stability and lowering power losses. The simulation results demonstrate lower network losses and better voltage profiles. Additionally, the study takes into account how greenhouse gasses affect the optimization process. [153] introduced an optimal network reconfiguration method for large-scale distribution systems using the Harmony Search Algorithm. The approach effectively minimized power losses and improved system reliability, showcasing the algorithm's potential for network reconfiguration in power systems.

The hybrid approach was presented by [154] with the goal of placing capacitors and EV charging stations as efficiently as possible while maintaining dependability and minimizing expenses and losses. Improved grid reliability and financial gains were demonstrated by validation on IEEE systems. Within a network of radial distribution, [155] provide an energy management system for EV fast charging stations that uses a photovoltaic distributed generator to optimize energy charging stations that integrate Grid-to-vehicle (G2V) and Vehicle-to-Grid (V2G) technologies is proposed in [156]. Their strategy seeks to maximize charging and discharging patterns while boosting grid stability, cutting expenses, and increasing energy efficiency. [157] proposed a profit-sharing plan for EV charging and discharging, which improved grid-to-EV parking operators communication. An IEEE-33 bus model and Saudi Arabian Traffic patterns are used in the study to lower carbon emissions, enhance energy management, and increase network stability.

2.4.1 Practical Challenges and Solutions in EVCS Placement

1. **Load Uncertainty:** Load uncertainty is a critical factor that can affect the optimal placement of EVCS. Since the number of EVs and their charging patterns are dynamic and dependent on factors like time of day, weather conditions, and user behavior, it is essential to incorporate load forecasting techniques that can predict these uncertainties. One can use advanced forecasting models such as machine learning-based approaches and probabilistic models to address this issue. These methods will help in accurately estimating the demand and in planning EVCS locations to avoid overloading specific areas of the grid.
2. **Grid Constraints:** The existing grid infrastructure may have limitations, including transformer capacity and feeder loading, that can affect the placement of EVCS. The need for grid reinforcement and integration of smart grid technologies is used to manage these constraints. Solutions such as demand-side management, peak shaving, and load balancing can be ways to alleviate the strain on the grid. Moreover, the use of distributed energy resources (DERs) like solar panels and energy storage systems can be explored which could reduce the burden on the grid and support the efficient operation of EVCS.
3. **Economic Factors:** Economic considerations are vital in determining the feasibility of EVCS placement. One can add the importance of evaluating the cost-effectiveness of installing and maintaining EVCS, considering factors like installation costs, electricity tariffs, and operational expenses in the study. Also examine incentive programs,

subsidies, and business models like pay-per-use or subscription services that could make the installation of EVCS more attractive for both private and public stakeholders.

To tackle the practical challenges listed above, the potential solutions are:

- a. **Technological Solution:** Smart charging infrastructure, predictive load management, and vehicle-to-grid (V2G) systems can mitigate the impact of load uncertainty and grid constraints.
- b. **Operational Solution:** The use of dynamic pricing, time-of-use tariffs, and real-time grid monitoring systems to optimize charging station operation and reduce strain on the grid.
- c. **Economic Solution:** Public-private partnerships, incentives, and subsidies can facilitate the deployment of EVCS, while cost-sharing models and financial assessments will guide economically viable placement decisions.

2.5 Literature Review on Impact of DG Placement

Voltage instability is a significant issue for modern power networks since there isn't enough capacity for transmission and generation to keep up with demand [158-159]. The issues that traditional power networks face, such as the requirement for improved system voltage stability (VS), have given rise to distributed generation as a potentially viable solution. Due to its various benefits, including the capacity to reduce voltage dips and offer auxiliary services to the utility, distributed generation has been more and more integrated into distribution networks throughout time [160]. Furthermore, a significant increase in electricity generation from renewable energy sources (RES) is expected to soon satisfy demand [161]. Therefore, power systems must be continuously monitored and regulated using the voltage stability indices (VSI). Due to its inherent uncertainties, the growing usage of renewables in microgrids and distribution networks is resulting in voltage instabilities.

In [162], authors have presented innovative strategies to address the challenges associated with optimal distributed generation (DG) placement. The loss sensitivity factor (LSF) was used in one study to recognize the best places for DG units, while the least cost analysis (LCA) algorithm was used to identify the ideal sizes. The enhanced algorithm provides a practical approach for integrating renewable energy sources into the grid by minimizing power losses and enhancing voltage stability [163]. An improved Moth Flame Optimization

algorithm was presented in another study to address battery energy storage systems and the best locations for numerous dispatchable and non-dispatchable DGs. In [164] authors, proposed the enhanced algorithm viable way to integrate renewable energy sources into the grid by efficiently reducing power losses and improving voltage stability. A comprehensive review of AC transmission grid code requirements and the role of FACTS devices in integrating renewable power plants was presented in [165]. The impact of electric vehicles on distribution system voltage stability and its enhancement through optimal distributed generation placement was investigated in [166]. A detailed review and comparison of voltage stability indices based on analytical methods and formulations in renewable-dominated power systems was discussed in [167]. Voltage stability analysis of modern power systems considering wind energy conversion systems was presented in [168], highlighting the influence of renewable energy integration on system stability performance. Numerous techniques have been documented in the literature to measure and categorize the phenomena of voltage instability. A novel optimal power flow model for the efficient operation of hybrid power networks was proposed in [169], focusing on improving system performance and operational efficiency under varying network conditions. A multi-stage voltage control optimization strategy for distribution networks considering active and reactive power co-regulation of electric vehicles was presented in [170], demonstrating improved voltage regulation and network stability. An enhanced line-based voltage stability index for static voltage stability assessment of electricity networks was introduced in [171], providing effective identification of weak buses and critical operating conditions in power systems.

In such instances, the stability indicator readings fluctuate between 0 and 1. When a contingency occurs and the power system is incapable of maintaining a sufficient voltage on entire buses, this is known as voltage instability. Thus, VSI has been shown to significantly improve power system stability when added to optimum power flow problems. To ascertain if a line can transmit the required power in this situation, several line indices have been proposed. A power system's VS is evaluated using a number of indices; the closer the parameter is to instability, the higher the value. The evaluation and comparative analysis of various voltage stability indices for power system applications were presented in [172]. The study analyzed the effectiveness of different indices in identifying weak buses and assessing voltage stability conditions under varying operating scenarios. A comprehensive review of advanced intelligent optimization algorithms for multi-objective optimal power flow in future power systems was discussed in [173]. The study highlighted the significance of

modern optimization techniques in improving system performance, minimizing losses, and enhancing voltage stability in renewable-integrated power networks.

An improved hybrid optimization algorithm for integrated energy distribution network systems was proposed in [174]. The study focused on minimizing voltage deviation, line losses, and operational costs while improving overall network efficiency and stability. Optimal placement of FACTS devices in transmission networks using Power Stability Index (PSI) and Fast Voltage Stability Index (FVSI) was investigated in [175]. The study demonstrated the effectiveness of stability indices in determining suitable locations for FACTS devices to enhance voltage stability and improve power system performance.

The trade-off between system security and economy is known as optimal power flow (OPF), which is the computation of the system's optimum control variables. The major aim of OPF is to examine the optimum state of the parameters within the operating constraints. A comprehensive review of optimal power flow approaches for hybrid power systems using various metaheuristic optimization techniques was presented in [176]. A hybrid Harmony Search algorithm integrated with Differential Evolution and Lévy Flight for engineering optimization applications was proposed in [177]. Optimization of radial distribution systems considering distributed generation and electric vehicle charging using the Spotted Hyena optimization approach was investigated in [178], focusing on improving voltage profile and reducing system losses. Bio-inspired optimization techniques for enhancing frequency stability in microgrids with electric vehicle support were discussed in [179], emphasizing the sustainability of renewable energy systems. A comparative review of various voltage stability indices and their applications in power system stability assessment was presented in [180].

Recent studies have focused on voltage stability enhancement and optimization techniques for modern renewable-integrated power systems. Hybrid transmission schemes for improving static voltage stability under varying operating conditions were presented in [181]. A novel World Cup Optimization (WCO) algorithm inspired by FIFA World Cup competitions was proposed in [182], and its application for optimal pitch angle control in hybrid PV/wind energy systems was discussed in [183]. A comprehensive review on optimal placement and sizing of distributed generation in distribution systems using multi-objective optimization techniques was presented in [184]. An improved chaotic WCO algorithm for energy supply configuration applications was investigated in [185].

Voltage stability assessment using advanced voltage stability indices has also been widely studied. A Unified Loadability Quality Factor (ULQF) for identifying weak buses and assessing system loadability was introduced in [186], while a detailed survey on voltage stability indices for transmission and distribution systems was presented in [187]. Particle Swarm Optimization (PSO), introduced in [188], has been extensively applied in engineering optimization problems, and its applications in solar energy systems were comprehensively reviewed in [189]. These studies highlight the importance of optimization algorithms and voltage stability assessment techniques for enhancing the performance and reliability of modern power systems.

The more electric vehicles (EVs) and RES are included in distribution system, the more complex the issue becomes. [190] provides a comprehensive overview of the current research on the optimal placement of Combined Heat and Power (CHP) systems in energy networks, aiming to highlight the methodologies, challenges, and advancements in this field. The ant lion optimization algorithm is discussed in [191-192] by emphasizing the economic and technical advantages of using this approach for DG placement. It might highlight how integrating nodal electricity prices into the optimization leads to more cost-effective and efficient network planning. Distributed generation (DG) placement in distribution systems has been widely studied using various optimization techniques to reduce power losses and improve voltage profile. In [193], a Genetic Algorithm (GA)-based method was proposed for optimal DG placement in distribution networks. A multi-objective approach using Simulated Annealing (SA) for optimal placement of multiple DGs in the IEEE 33-bus system was presented in [194], which improved voltage stability and reduced losses. In [195], the Artificial Bee Colony (ABC) algorithm was employed for optimal placement and sizing of DG units, demonstrating effective loss minimization and enhanced system performance.

The modern electrical power system requires a secure and reliable power transmission and distribution infrastructure due to the continuously increasing demand for electricity. As a result, voltage stability (VS) has become one of the major concerns for improving overall system performance and ensuring secure network operation. Consequently, advanced optimization techniques are increasingly being utilized to enhance the stability and operational efficiency of distribution systems.

In this work, a metaheuristic optimization approach is proposed for improving the voltage stability of the distribution network through the optimal placement of distributed generation (DG) units. The proposed method employs the World Cup Optimization (WCO) algorithm for determining the optimal locations of solar PV and wind generation sources within the distribution system. The WCO algorithm is distinguished by its novel tournament-based strategy, which incorporates dynamic competition among candidate solutions. This mechanism improves the balance between exploration and exploitation, resulting in better convergence characteristics and enhanced robustness.

Furthermore, the WCO algorithm is highly effective in solving complex and nonlinear optimization problems associated with DG placement. Compared to conventional optimization techniques, the proposed approach offers improved solution quality and system performance. Based on the literature survey, it is observed that the WCO algorithm has not previously been applied for the optimal siting of DG units in distribution systems. Therefore, this research investigates the effectiveness of the WCO technique for enhancing voltage stability, minimizing power losses, and improving the overall operational performance of the distribution network.

2.5.1. Influence of Cable Material and Feeder Characteristics on Loss Reduction

The effectiveness of optimal DG placement in reducing active power losses is consistent across various distribution network configurations. However, the magnitude of loss reduction is significantly influenced by system parameters, particularly the conductor material and feeder length. Aluminum conductors, due to their higher electrical resistivity compared to copper, inherently experience greater I^2R losses under similar loading conditions. Our comparative analysis demonstrates that while both copper and aluminum feeders benefit from reduced current flow through local generation, the relative improvement in loss reduction is more pronounced in aluminum-based systems. This indicates that the proposed WCO-based DG placement strategy can yield even greater operational efficiency in networks characterized by long feeders and high-resistance conductors, where distribution losses are typically more severe. Additionally, as DG output increases, upstream line current decreases, leading to a nonlinear reduction in losses validating the principle that minimizing current through resistive paths significantly enhances energy efficiency.

2.5.2. Limitations of Tap Changers and Advantages of DG-Based Voltage Support

Traditional voltage regulation devices, such as on-load tap changers (OLTCs), are effective for maintaining voltage at the substation or feeder head but offer limited control over voltage conditions at distant buses. Tap changers regulate voltage at a single control point and are typically slow to respond to rapid or localized variations in load and generation. In contrast, the proposed approach enables localized voltage support through the optimal placement of distributed generation units across the feeder. By injecting power closer to load centres, especially at buses electrically remote from the substation, the method helps mitigate voltage drops and flatten the voltage profile more effectively than OLTCs alone. Moreover, unlike conventional regulation schemes, the proposed WCO-based optimization method concurrently addresses real power loss minimization, making it a dual-purpose solution that enhances both voltage stability and energy efficiency in distribution systems. This integrated benefit positions the method as a valuable complement to existing utility practices.

2.6 Literature Review for Inverter Based Renewable Energy Integration

Renewable technologies are developing quickly as a result of the growing demand for sustainable and clean energy on a worldwide scale. Due to their dependability, environmental friendliness, scalability, and falling installation costs, solar photovoltaic (SPV) systems have become the most widely used. Grid-connected SPV systems are especially favored because they facilitate power exchange between the generating system and the utility grid, providing dependable and economical operation. Recent advancements in solar photovoltaic technology and power quality improvement techniques have been widely reported in the literature. Solar cell efficiency enhancement and performance comparison of photovoltaic technologies were comprehensively presented in [196]. Active power filters for improving power quality by mitigating harmonics, reactive power, and current distortions in electrical systems were reviewed in [197]. However, there are a number of technical difficulties when integrating SPV systems into the electrical grid, particularly when there are non-linear loads at the PCC. Harmonics are introduced into the system when non-linear loads pull non-sinusoidal currents. Standards and recommended practices for harmonic control in electric power systems, including permissible harmonic limits and power quality requirements were discussed in [198]. IEEE-519 standards state that eliminating harmonic distortion and preserving sinusoidal grid currents are essential for safe and effective grid operation.

Accurate synchronization between the grid voltage and inverter current is essential to ensure

effective power exchange in a grid-connected solar photovoltaic (SPV) system. The overall performance of the system largely depends on the control strategy adopted for inverter operation. To inject a clean sinusoidal current into the utility grid, various advanced control approaches have been developed. These techniques typically generate reference current signals according to real-time system conditions such as grid voltage, frequency, and load dynamics. The generated references are then processed by the controller to produce appropriate gating pulses for the power electronic switches of the inverter, thereby ensuring stable operation, improved power quality, and reliable grid interaction.

Phase-Locked Loop (PLL)-based methods have historically been used extensively for grid synchronization because of their straightforward implementation and adequate steady-state accuracy. Phase inaccuracy, sluggish dynamic response, and increased harmonic injection are some of the performance issues that PLL structures display when they are subjected to low Short Circuit Ratio (SCR), frequency drift, voltage imbalance, or distorted grid voltages. In weak-grid circumstances with substantial penetration of renewable energy sources, these constraints become more noticeable.

Phase-Locked Loop (PLL)-based synchronization techniques are widely used in grid-connected power electronic systems for phase and frequency estimation. However, conventional PLLs may exhibit poor performance under distorted and unbalanced grid conditions. To address these issues, Frequency Locked Loop (FLL)-based methods, particularly the Second-Order Generalized Integrator FLL (SOGI-FLL), have gained attention due to their improved frequency tracking and harmonic rejection capability [199 - 201]. Compared to classical PLLs, SOGI-FLL structures provide better robustness and effective filtering of fundamental components.

Recent advancements in three-phase PLL techniques were reviewed in [199], while the adaptive filtering characteristics of synchronous reference frame PLLs were discussed in [200]. An improved SOGI-FLL error-and-hold algorithm for enhanced dynamic response during voltage sags and swells with low computational burden was presented in [201]. Although SOGI-based methods offer improved synchronization performance, their effectiveness may still be affected under severe harmonic distortion and nonlinear loading conditions.

To improve dynamic stability and disturbance rejection, adaptive estimation and selective

filtering techniques have been added to sophisticated synchronization algorithms in more recent years. Specifically, direct extraction of the fundamental frequency component is made possible by attenuating harmonic distortion by incorporating a Complex Band-Pass Filter into the FLL structure. By incorporating harmonic-selective filtering directly into the synchronization loop, the CBF-FLL technique enhances noise immunity, weak-grid tolerance, and transient response in contrast to traditional PLL-based techniques that mainly rely on phase error minimization.

Advanced synchronization and control techniques based on Complex Bandpass Filter Frequency Locked Loop (CBF-FLL) and SOGI-FLL structures have been widely applied in renewable energy-based microgrids. A stator synchronization and dynamic control strategy for a wind-driven DFIG-battery-based microgrid using CBF-FLL filtering was presented in [202], demonstrating improved synchronization performance for rural electrification applications. In [203], CTanh-LMS and CBF-FLL techniques were implemented for load compensation and grid synchronization in a solar PV-battery energy storage (BES)-based microgrid. Furthermore, a CBF prefiltered SOGI-FLL-based synchronization method for the control of DFIG-SPV-BES microgrids was proposed in [204], showing enhanced synchronization accuracy and dynamic performance under distorted grid conditions.

Recent studies have focused on enhancing synchronization, stability, and power quality in renewable energy based distributed generation and microgrids. The contributions in recent literature provide significant advancements in adaptive and resilient converter control under disturbances, intermittency, and nonlinear loading. [205] proposed an adaptive power management strategy capable of maintaining voltage and frequency stability under faults and DC-offset conditions. An ICCF-PLL based strategy was developed for hybrid WECS-SPV-BSS systems, demonstrating reliable phase tracking under harmonic distortion. Although effective, PLL-based techniques inherently suffer from sensitivity to severe nonlinearities and weak grid scenarios, where filtering capability becomes limited. In [206], the authors extended adaptive regulation to isolated renewable systems with intermittency, achieving smoother dynamic performance. A fast and robust control solution for islanded microgrids with EV charging was later introduced in [207], demonstrating improved transient recovery and DC-link regulation. Similarly, [208] addressed power quality improvement in isolated microgrids through adaptive compensation techniques. While these

approaches effectively enhance converter resilience, synchronization accuracy in distorted or weak grids remains largely dependent on conventional estimation mechanisms.

Further researchers have attempted to strengthen grid interaction by refining synchronization and converter strategies. [209] developed active power coefficient control to mitigate distortion effects, whereas [210] proposed a resilient architecture for PV-wind-battery systems under unbalanced voltages for improved harmonic performance through optimized PLL-based techniques. Power quality improvement in grid-connected photovoltaic systems using an optimal PLL-based control strategy was presented in [211]. A high-gain noncoupled DC–DC boost converter with reduced stress and ripple for renewable energy systems was designed and analysed in [212]. Three-phase Frequency Locked Loop (FLL) techniques for grid synchronization were comprehensively studied in [213]. The design and performance assessment of residential photovoltaic systems under varying weather conditions were investigated in [214]. Simplified design and modelling of boost converters for photovoltaic systems were discussed in [215]. However, PLL-derived structures still exhibit sensitivity to harmonics, noise, and frequency deviations. Power quality improvement techniques and control strategies for modern power systems were discussed in [216]. Various Maximum Power Point Tracking (MPPT) techniques for photovoltaic systems, including comparative analysis and optimization of the Perturb and Observe (P&O) method, were presented in [217]-[219]. In addition, a hybrid optimization approach for optimal placement of electric vehicle charging stations (EVCS) in distribution networks considering voltage stability was proposed in [220]. Voltage-sourced converters (VSCs), their control, and applications in modern power systems were discussed in [221]. Grid synchronization techniques using multiresonant frequency-locked loop (FLL) methods and predictive control strategies for inverters were presented in [222], [223]. Different MPPT techniques for solar PV systems and power electronic control methods for maximum energy harvesting were analysed in [224], [225]. Control strategies for active power filters aimed at power quality improvement were discussed in [226], [227]. An IoT-supported solar EV charging solution was proposed in [228], while voltage stability analysis considering wind energy conversion systems was investigated in [229].

Nevertheless, there is still a lack of research on the use of a stand-alone CBF-FLL technique designed especially for grid-connected solar PV systems.

Developing and modeling a control algorithm for a double-stage, three-phase grid-connected

SPV system using the CBF-FLL technique is the primary goal of this project. The suggested control technique is intended to maintain low THD levels in grid currents and guarantee stable operation under a variety of abnormal conditions, such as zero irradiance, abrupt changes in non-linear demand, and variable solar irradiance.

2.7 Challenges and Directions for Future Research

The operating conditions of the power system are always changing since it is dynamic. System topology, or the linkages between networks, also varies regularly. Uncertainties regarding the sharp increase in electricity demand. The operation of power system components is getting closer to their design limits. Considering the overview of the literature survey on integration of highly penetrated renewable energy resources with the grid, several possible challenges and directions for future research are listed below:

- High penetration of renewable energy sources adds to power quality and control problems.
- Reactive power management in present day power system is assuming great significance in view of the overloading of transmission lines, unacceptable system voltage profile, high transmission and distribution losses and voltage instability/collapse.
- For a system to maintain a desirable voltage profile, to reduce transmission and distribution losses and to prevent voltage instability/collapse, timely reactive power planning and efficient scheduling is necessary.
- Voltage stability analysis with integration of high penetration of renewable energy sources.
- Requirement of Proper mathematical modelling of transmission and distribution networks.
- Voltage stability of specific grid-feeding converter applications, i.e., wind farm, PV solar and HVDC links.
- In terms of objective function in optimization problem, the objectives considered in most studies are active power loss and voltage magnitude. The voltage stability problem has not been thoroughly studied.
- Monitoring of voltage stability online. Online power system stability evaluation has been implemented using machine learning-based data-driven approaches thanks to the implementation of PMU.
- Most studies have not taken into account the payment for ancillary services related to reactive power, which is not included in deregulated electricity markets with multiple

market participants. Designing the reactive power market while taking into account the participation of renewable energy sources is a challenge.

- Identifying Long Term Voltage Stability Caused by Distribution Systems vs Transmission Systems.
- Over-voltages due to large penetration of PVs. This can be solved by Coordinated operation of multiple lead-acid battery ESSs.
- Design of controller for fast reactive power compensation.
- Agent-based identification and control of voltage emergency situations.
- Optimal setting of reactive compensation devices to enhance voltage stability.
- Long term voltage stability with integration of wind energy system.
- Short-term voltage stability in the presence of VSC has been comparatively less investigated.
- Local identification of voltage instability from load tap changer response.
- Impact of electric vehicle fast charging on power system voltage stability.
- Development of a new voltage stability index.
- Event generated var and voltage control method for power grids with connection of large-scale renewable energy resources such as wind, solar etc.
- Application of big data techniques.
- Design of reactive power market considering participation of renewable energy resources.

2.8 Summary of Literature Review

- The literature review emphasizes the growing importance of voltage stability in modern power systems, particularly due to the increasing integration of renewable energy sources (RES), distributed generation (DG), and electric vehicle charging stations (EVCS). Voltage instability has historically been a major cause of large-scale blackouts, necessitating the development of reliable assessment and control techniques. Various Voltage Stability Indices (VSIs) have been proposed to evaluate system stability, which are broadly classified into Jacobian-based, system variable-based, and line, bus, and overall indices. While Jacobian-based methods provide accurate identification of voltage collapse points, their high computational complexity limits real-time application. In contrast, system variable-based indices such as FVSI, LSI, and LSF offer faster and simpler solutions, making them suitable for practical implementation.

- The integration of RES introduces significant challenges, including intermittency, reduced reactive power support, and voltage fluctuations, thereby increasing the risk of instability. In this context, optimal placement and sizing of DG units and EVCS play a crucial role in improving voltage profile, reducing losses, and enhancing system reliability. Numerous optimization techniques, such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and other meta heuristic techniques have been effectively applied to solve these complex, multi-objective problems. Additionally, the use of Phasor Measurement Units (PMUs) and Wide Area Measurement Systems (WAMS) enables real-time monitoring of system conditions. Recent advancements in hybrid optimization algorithm, machine learning and cyber-physical systems have further improved the capability for fast and accurate voltage stability prediction.
- Moreover, inverter-based renewable integration has introduced new challenges related to synchronization and power quality, leading to the development of advanced control techniques. Despite significant progress, several research gaps remain, including the need for computationally efficient real-time VSI methods, integrated optimization of DG and EVCS, and improved reactive power management strategies. These challenges provide strong motivation for the present research work focused on enhancing voltage stability in renewable-rich power systems.

2.9 Research Gap

Existing literature on distribution-system planning and control reveals critical shortcomings in the coordinated integration of EV charging infrastructure and renewable energy sources (RES). The proposed research specifically targets and bridges the following key gaps:

- ✓ **Absence of Voltage Stability in EVCS Placement:** Current studies predominantly focus on power loss minimization and economic factors, neglecting voltage stability constraints critical for high EV penetration scenarios.
- ✓ **Limited Multi-Objective Optimization Frameworks:** Very few works simultaneously optimize PV-wind placement considering voltage stability using comprehensive multi-objective approaches.
- ✓ **Inadequate Robust Inverter Synchronization:** Gap persists in adaptive Phase-Locked Loop (PLL) techniques for accurate reference current estimation under grid disturbances and renewable intermittency. **Insufficient Weak-Grid Operation Analysis:** Weak grid conditions (low Short Circuit Ratio) and low-inertia scenarios

remain poorly addressed during RES integration, limiting practical deployment.

2.10 Research Objectives

Three main objectives addressed in this thesis are:

- ✓ Development of a novel hybrid Coati Optimization Algorithm- Pelican Optimization Algorithm (COA-POA) for optimal placement of EVCS in the distribution system.
- ✓ Application of World Cup Optimization (WCO) for optimal allocation of Solar PV and Wind generators to enhance voltage profile and reduce power losses.
- ✓ Design and implementation of an advanced complex band pass filter frequency lock loop (CBF-FLL) based controller for: Real-time voltage regulation, power quality enhancement, fast grid synchronization.

2.11 Author's Contribution Based on Literature Survey

- Identified the critical limitations of existing literature in addressing voltage stability constraints during EVCS placement, where most studies focus primarily on loss minimization and economic factors.
- Developed a comprehensive multi-objective hybrid framework that considers optimal placement of EVCS, solar PV, and wind DG units, incorporating voltage stability indices along with loss and voltage profile improvement.
- Proposed the use of voltage stability indices (FVSI, LSI, LSF) as objective/decision parameters for accurate identification of weak buses and enhancement of system stability.
- Introduced a coordinated planning approach integrating EVCS and renewable energy sources to improve grid resiliency, reduce active power losses, and enhance voltage regulation.
- Addressed the gap in inverter synchronization by emphasizing robust Grid-Following (GFL) inverter control using FLL-based techniques, ensuring stable operation under weak grid conditions and nonlinear loading.
- Incorporated realistic operating scenarios, including renewable intermittency, variable load demand, and weak grid conditions, to evaluate system performance comprehensively.

2.12 Original Contributions of the Thesis

The original and significant contributions of the present Ph.D. research are summarized as follows:

- A novel hybrid optimization framework based on Coati Optimization Algorithm (COA) and Pelican Optimization Algorithm (POA) is developed for the optimal placement of Electric Vehicle Charging Stations (EVCS) with direct consideration of voltage stability indices, which is not addressed in existing EVCS planning literature.
- A World Cup Optimization (WCO)-based methodology is proposed for the simultaneous optimal placement of solar PV and wind generation in EVCS-integrated distribution systems, enabling enhanced voltage stability, power loss reduction, and renewable hosting capacity improvement.
- An advanced Complex Band-Pass Filter based Frequency Locked Loop (CBF-FLL) controller designed for reference current estimation in grid-connected inverters is the novelty, which has not been reported in earlier literature. Robust inverter control strategy is developed to ensure stable PCC voltage, fast synchronization under distorted and weak grid conditions, THD compliance with IEEE-519 standards.
- The research provides Indian grid-relevant solutions considering:
 - Electric vehicle charging growth
 - Renewable integration policies
 - Voltage band limits specified in Indian Grid Code
- The thesis offers a comprehensive mitigation framework for voltage instability caused by high EV penetration and renewable intermittency, bridging the gap between distribution planning and real-time voltage control.
- Implemented and validated the proposed methodology using MATLAB/Simulink (SimPower Systems) on the standard IEEE distribution system, ensuring practical relevance and applicability.

2.13 Summary

In summary, the literature highlights significant progress in voltage stability assessment, optimal placement of EVCS and DG, and integration of renewable energy in distribution systems. Various Voltage Stability Indices (VSIs) and optimization techniques, including hybrid algorithms, have been effectively used to improve voltage profile, minimize losses, and enhance system performance.

The studies also emphasize the impact of renewable energy and EV charging loads, which introduce variability and uncertainty into the system. Advanced inverter-based control strategies have been developed to improve grid synchronization, voltage regulation, and power quality.

However, gaps still exist in the simultaneous consideration of voltage stability in EVCS and DG placement, along with the need for robust multi-objective optimization and adaptive control strategies under weak grid conditions. These limitations form the basis and motivation for the present research work.

CHAPTER–3

OPTIMAL EVCS PLACEMENT USING HYBRID OPTIMIZATION

This chapter presents an advanced approach for the optimal placement of Electric Vehicle Charging Stations (EVCS) in distribution systems using a novel hybrid Coati Optimization Algorithm-Pelican Optimization Algorithm (COA-POA). With the increasing penetration of electric vehicles, EVCS integration introduces significant challenges such as voltage deviation, increased power losses, and degradation of voltage stability in distribution networks.

Unforeseen and random placement of EVCS can severely affect system performance, particularly in radial distribution systems with limited capacity. Therefore, an efficient and intelligent optimization framework is required to determine the optimal locations of EVCS while maintaining system stability and operational efficiency.

In this context, the proposed hybrid COA-POA technique leverages the strengths of both algorithms, where COA contributes to effective global exploration and POA enhances local exploitation capabilities. This combination ensures a better balance between exploration and exploitation, resulting in improved convergence speed and higher-quality optimal solutions.

The optimization framework considers multiple objectives, including minimization of voltage deviation, enhancement of voltage stability indices (VSI), and reduction of active power losses. The performance of the proposed method is validated using the IEEE 33-bus distribution system under various loading conditions.

3.1 Introduction

Growth in population, industrialization, and urbanization are led to increase the electrical demand. Escalating need for electrical energy is satisfied by Renewable Energy Sources (RES). Moreover, the power generation from RES is expected to increase drastically to meet

demand in the near future. Owing to the development of battery technology, Electric vehicles (EVs) are proposed to overcome the limitations of traditional transportation system. As the demand for EVs gets varied due to driving patterns and distance. EVs can be powered from charging stations, which are excited by the distribution network. The EV is considered a single-phase load thus it can be connected to any phase in a three-phase line, causing line overloading. The rising demand for power in EV charging station is accomplished by the addition of RES. Increasing penetration of RES in the distribution networks and microgrids are resulting voltage instabilities owing to the renewable uncertainties.

Moreover, transmission capability of the power grids reaching its limits due to higher power consumption and reforms in electricity market. Occurrence of fault in the power system is also the main cause for voltage instabilities that may collapse entire power network at specific locations. Over the past years, numerous authors studied the impact of EVs in the distribution network. The EVs are considered as non-linear loads hence, the higher load demand has increased the issues in power system including voltage instability. An exponential growth of EVs have possesses new challenges in the distribution network. Excessive power requirements owing to the EV integration would causes voltage mismatches and power efficiency will cause negative impacts in the distribution network. Voltage stability analysis is a major tool to estimate the transmission capacity in a power system. Stability assessment of voltage helps to improve the system performance for ensuring safety and reliability of power supply.

Several methods have been reported in existing literatures for quantifying and qualifying the voltage instability phenomenon. In such cases, the values of stability indicator vary in between 0 and 1. Voltage instability is the condition which power system is unable to maintain the acceptable voltage at all buses after occurring contingency. Hence, addition of VSI in optimum power flow problems has proven significant voltage stability enhancement in the power system. In this regard, several line indexes have been suggested to check the ability of the transmission line to transfer required amount of power. Several indexes are considered for voltage stability assessment in power system; fast voltage stability index (FVSI) is used for examining bus where the voltage collapse occurs. Moreover, the voltage stability on each line is examined through line stability index, higher value of the parameter

indicates the closeness to the instability. The line stability factors will check voltage stability of lines in distribution network.

The computation of the system's optimal control variables, or the trade-off between system economy and security, is known as optimal power flow (OPF). Examining the optimal condition of the parameters within the operational limitations is a major goal of OPF [125]. In [126], an OPF with the goals of real power loss, voltage variations, and static voltage stability is described. Initially, each of these objective functions is solved individually; thereafter, the slap swarm optimizer is used to accomplish these objectives. The optimization algorithm for DG and electric vehicle-connected distribution power systems, which estimates system performance under changing load profiles, was proposed by the author in [127]. In [128], a voltage stability enhancement technique based on optimization algorithms that takes into account both continuous and discrete control variables is employed. As these optimization approaches are more efficient for specifying the weakest bus as the preferred location for the placement of DGs.

In particular, a lot of works have already been done on voltage stability enhancement in distribution system. Also, situation becomes more complex with increasing penetration of renewable energies and EVs in distribution system. However, only limited studies have been made on voltage stability enhancement of EV and RES connected distribution network. The novelty of this work lies in the development of a hybrid Coati Optimization Algorithm Pelican Optimization Algorithm (COA-POA) for optimal EVCS placement in distribution networks. The proposed approach effectively combines the strong exploration capability of COA with the efficient exploitation ability of POA, ensuring a balanced search process. This hybridization enhances convergence speed, avoids local optima, and significantly improves voltage stability and system performance compared to conventional methods.

3.2 Problem Statement-1

Electric vehicle (EV) adoption is posing serious problems for power distribution systems, mainly because of the increased energy demand and possible effects on voltage stability. It is imperative to properly optimize the EV charging stations (EVCS) integration of grid in order to guarantee effective energy distribution, and ensure the distribution system's voltage stability. When EV charging stations are positioned incorrectly, the power network may experience overloads, voltage instability, and decreased dependability, which could impact grid performance and customer service quality. To address these issues, voltage stability

must be taken into consideration when determining the ideal location for EVCS within a distribution network. It is a multi-objective optimization problem. For the grid to meet the growing demand for EV charging while keeping appropriate voltage limits, a variety of factors must be carefully balanced. In recent years, significant research attention has been focused on the impact of fluctuating EV loads on power system performance. Consequently, the optimal placement of electric vehicle charging stations (EVCSs) has become a major area of concern. To address this issue, a novel hybrid optimization strategy combining two optimization techniques is proposed for determining the optimal EVCS locations.

3.3 Proposed Methodology

One of the main problems with the modern electrical grid is voltage instability. The present electrical power system is in terrible need of secure electrical power transmission infrastructure because of the steadily increasing demand for electricity. Therefore, voltage stability needs to be the main focus for the improvement of the system performance. Thus, the suggested technique which makes use of metaheuristic algorithms is designed to improve the stability of the distribution network. Here, the hybrid coati and pelican optimization algorithm provide uniqueness. The best site for an EV charging station is examined in this suggested work using a hybrid Coati and Pelican optimization method. The Hybrid Coati-Pelican optimization technique is a novel metaheuristic algorithm that combines the global exploration capabilities of the Coati Optimization Algorithm (COA) with the efficient local exploitation of the Pelican Optimization Algorithm (POA). Proposed algorithm enhances diversity by integrating COA's broad search with POA's improvement, preventing premature convergence and increasing the likelihood of finding the global optimum. It improves convergence through adaptive switching between COA and POA phases, enabling efficient navigation of the search space. The modified IEEE-33 bus distribution network is used to validate this suggested approach. A forward-backward power flow method has been applied to compute load flow. The convergence criterion is compared with the other latest optimization techniques. The results of the simulation validate the effectiveness and performance of the hybridized optimization technique. The MATLAB/Simulink tool is used to implement this suggested approach.

3.3.1 Proposed Methodology for Problem Statement-1

✓ Hybrid Optimization Framework for EVCS Placement

- The proposed research develops an advanced methodology for optimal Electric Vehicle Charging Station (EVCS) allocation in distribution networks through the following key contributions:
- Novel Hybrid Coati Optimization Algorithm (COA) and Pelican Optimization Algorithm (POA): A sophisticated hybrid metaheuristic is formulated by integrating the exploration capabilities of COA (inspired by coati foraging behavior) with the exploitation precision of POA (mimicking pelican hunting strategies), achieving superior convergence and global optima search for complex multi-objective EVCS placement problems.
- Comprehensive Objective Function: Simultaneously optimizes power loss minimization, minimization of voltage deviation and voltage stability enhancement, under high EV penetration scenarios, addressing critical gaps in existing literature.
- Validation on Benchmark Systems: The IEEE 33-bus radial distribution system serves as the primary testbed for rigorous performance evaluation, with comparative analysis against individual algorithm demonstrating superior results in loss reduction and voltage profile improvement.

3.3.2 Coati Optimization Algorithm (COA)- Exploration Phase (Global Search) [140]

- COA is a metaheuristic inspired by the foraging and social behavior of coatis, particularly their tendency to search over large areas with high mobility.
- COA provides diverse solution sampling by generating position updates using stochastic movement patterns that allow wide exploration of the search space.
- This exploration is important in EVCS placement because the search landscape is highly non-convex, influenced by voltage deviation, power losses, and VSI constraints.
- Therefore, COA ensures that the algorithm identifies multiple feasible regions across all 33 buses rather than prematurely converging to local minima.

3.3.3 Pelican Optimization Algorithm (POA)- Exploitation Phase (Local Search) [141]

- POA models the hunting strategy of pelicans, which involves detecting prey and performing a steep ‘diving attack’ to converge rapidly.

- From an optimization perspective, POA applies intensification by tightening the search around the best solutions generated during exploration.
- This refining capability is essential because once the candidate EVCS locations are identified, the algorithm must fine-tune bus position to achieve minimal voltage deviation, loss reduction, and improved VSI.
- Thus, POA provides the strong exploitation capability needed for convergence to the global optimum.

3.3.4 Hybrid COA- POA (Proposed)

- EVCS allocation is a multi-objective non-linear problem: locating a high-demand EV load at the wrong bus worsens voltage stability indices and increases losses.
- COA contributes a high degree of global exploration, ensuring scanning of all possible bus combinations.
- POA strengthens local exploitation, refining the best candidates for final optimal siting.
- The hybrid approach balances exploration and exploitation, resulting in faster convergence, reduced computational overhead, and more accurate EVCS placement. The detailed modelling of EVCS and hybrid algorithm is explained in section 3.5.

3.4 EV Charging Station Modelling

Reduction in fossil fuels and environmental degradation issues are the primary factors driving the popularity of electric Power system engineers face enormous challenges due to the demand for EV charging; therefore, demand for EVCS also get enhanced. The demand in charging station is based on number of EVs arrived to charge the vehicles. The energy demand in charging station is considered as follows;

$$D = \sum_{n \in N_k} E_{EV} \quad (3.1)$$

Where D denotes energy demand, E_{EV} indicates total energy required for to EV for N_k number of vehicles [135]. Constraints used in charging stations are as follows;

$$N_{EV} \leq N_C \quad (3.2)$$

$$P_{\min} \leq P \leq P_{\max} \quad (3.3)$$

$$SOC_{\min i} \leq SOC_i \leq SOC_{\max i} \quad (3.4)$$

Where, N_{EV} indicates number of EVs, N_C denotes number of chargers available in charging station, $P_{\min}$ signifies minimum power, $P_{\max}$ represent maximum power, SOC_i indicates SOC of i^{th} EV, $SOC_{\min i}$ denotes minimum SOC, $SOC_{\max i}$ represent maximum SOC. In this work, based on the power limits of EV batteries. The best planning is required to deploy EV charging station where they will best serve consumers with high charging demand. Furthermore, the voltage variation of the power system network must stay within legal bounds and power losses must be maintained as low as feasible. Maintaining a healthy voltage profile at every node is considered the goal, and this is achieved by minimizing voltage variation. These objectives are obtained by optimal allocation of charging station.

3.5 Hybrid Optimization Algorithm for Placement of EV Charging Station

In this work, hybrid COA and POA method is proposed for selecting optimal location for charging station placement. VSI and line stability are taken into consideration as an objective in this hybrid method. This method will select the optimal location for EV charging station with high voltage stability. Main objective of this hybrid method is to diminish average voltage deviation and to increase voltage stability in network. This method will select optimal location based on this objective. The voltage deviation [137] in the magnitude at all nodes are as follows;

$$f_1 = \frac{1}{N_n} \sum_{n=1}^{N_n} |1 - V_n|^2 \quad (3.5)$$

Where, N_n indicates number of nodes in IEEE 33 system and V_a denotes node a voltage. The VSI [138] is evaluated using below equation;

$$f_2 = |V_b|^4 - 4(P_b X_{ab} + Q_b R_{ab})^2 - 4(P_b X_{ab} + Q_b R_{ab})|V_b|^2 \quad (3.6)$$

Where, V_b denotes node b voltage, P_b indicates active power, X_{ab} signifies reactance in branches, Q_b represent reactive power and R_{ab} denotes resistance between nodes a and b . Hence, the combined hybrid objective function is formulated to simultaneously reduce voltage deviation index and to maximize VSI by combining both objectives into a single optimization framework. Mathematically, expressed as follows;

$$f = \left(Wf_1 + \frac{W}{f_2} \right) \quad (3.7)$$

Where,

f - Combined hybrid objective function.

f_1 - First objective function representing the minimization of voltage deviation in distribution system

f_2 - Second objective function representing the maximization of the voltage stability index (VSI) for improving system stability

W -Weighting factor used to balance the contribution of both objective functions in the hybrid optimization process.

The weighting factor W is used in the proposed hybrid objective function to control the contribution of both objective functions, namely voltage deviation minimization and voltage stability enhancement. The value of W is generally selected within the range of, $0 < W < 1$. In this work, the value of $W = 0.6$ is selected to provide an appropriate balance between voltage profile improvement and voltage stability enhancement. The final objective function of the optimization problem is formulated as:

$$F = \min (f) \quad (3.8)$$

Where the optimization algorithm searches for the minimum value of the combined objective function to obtain the optimal solution for the distribution system.

This proposed method combines COA and POA into a new algorithm. The exploration of phase of POA algorithm is combined with COA algorithm to obtain better results for placing charging station in an optimal location. Initialization is takes is place by COA algorithm. COA is a new optimization technique, this method mimics the hunting behaviors of coatis [139]. The coatis are a sophisticated animal that can fight and kill iguanas in addition to pursuing and avoiding predators. Random initialization of COA algorithm is as follows;

$$\left. \begin{array}{l} C_i : C_{ij} = L_j + R.(U_j - L_j) \\ i = 1, 2, \dots, N \\ j = 1, 2, \dots, m \end{array} \right\} \quad (3.9)$$

Where, m means total decision variables, C_i indicates bus position in i^{th} search space, R specifies random number, C_{ij} denotes j^{th} decision variable and N signify number of bus, U_j & L_j represents upper and lower bound of the j^{th} variable [140]. Population matrix is evaluated using below equation;

$$C = \begin{bmatrix} C_1 \\ \vdots \\ C_i \\ \vdots \\ C_N \end{bmatrix}_{N \times m} = \begin{bmatrix} C_{1,1} & \cdots & C_{1,j} & \cdots & C_{1,m} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ C_{i,1} & \cdots & C_{i,j} & \cdots & C_{i,m} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ C_{N,i} & \cdots & C_{N,j} & \cdots & C_{N,m} \end{bmatrix}_{N \times m} \quad (3.10)$$

Bus position is mathematically simulated using the below equation;

$$C_i^{p1} : C_{i,j}^{p1} = C_{ij} + R \cdot (I_j - I \cdot) C_{ij} \quad (3.11)$$

EVCS is placed in a random position in the search space. Coatis random position is simulated using the below equation,

$$C_i^{p1} : C_{i,j}^{p1} = \begin{cases} C_{i,j} + R \cdot (I_j^G - 1 \cdot C_{i,j}), & F_{iguana^G} < F_i \\ C_{i,j} + R \cdot (C_{i,j} - I_j^G), & \text{else} \end{cases}, \quad (3.12)$$

$$C_i = \begin{cases} C_i^{p1}, & F_i^{p1} \\ C_i & \text{else.} \end{cases} \quad (3.13)$$

The updated process results in new position, which is calculated for each increasing value of objective function in equation (3.12). In exploitation phase, bus position gets updated using POA method. Hybridization of COA and POA is done by using the below equation,

$$C_i^{p2} = L_j + R \cdot (U_j - L_j) \quad (3.14)$$

A random position is generated using the POA methods hunting characteristics [141] to obtain optimal position using (3.15) and (3.16).

$$C_{i,j}^{P2} = C_{i,j} + R \left(1 - \frac{t}{T} \right) \cdot C_{i,j} \cdot (2R - 1) \quad (3.15)$$

$$C_i = \begin{cases} C_i^{P2}, & F_i^{P2} \\ C_i & else. \end{cases} \quad (3.16)$$

Where, $C_{i,j}^{P2}$ specifies updated position based on POA exploitation phase, t signify iteration counter, T signifies a maximum number of iteration and F_i^{P2} indicates an updated objective function [142]. Iterations get repeated to get the optimal position for placing the EVCS. The minimum voltage deviation and high VSI bus is selected as optimum location based on COA-POA. This process gets stopped when this method obtained finest location in the IEEE 33 bus with specified values. Figure 3.1 represent the flowchart for hybrid COA-POA.

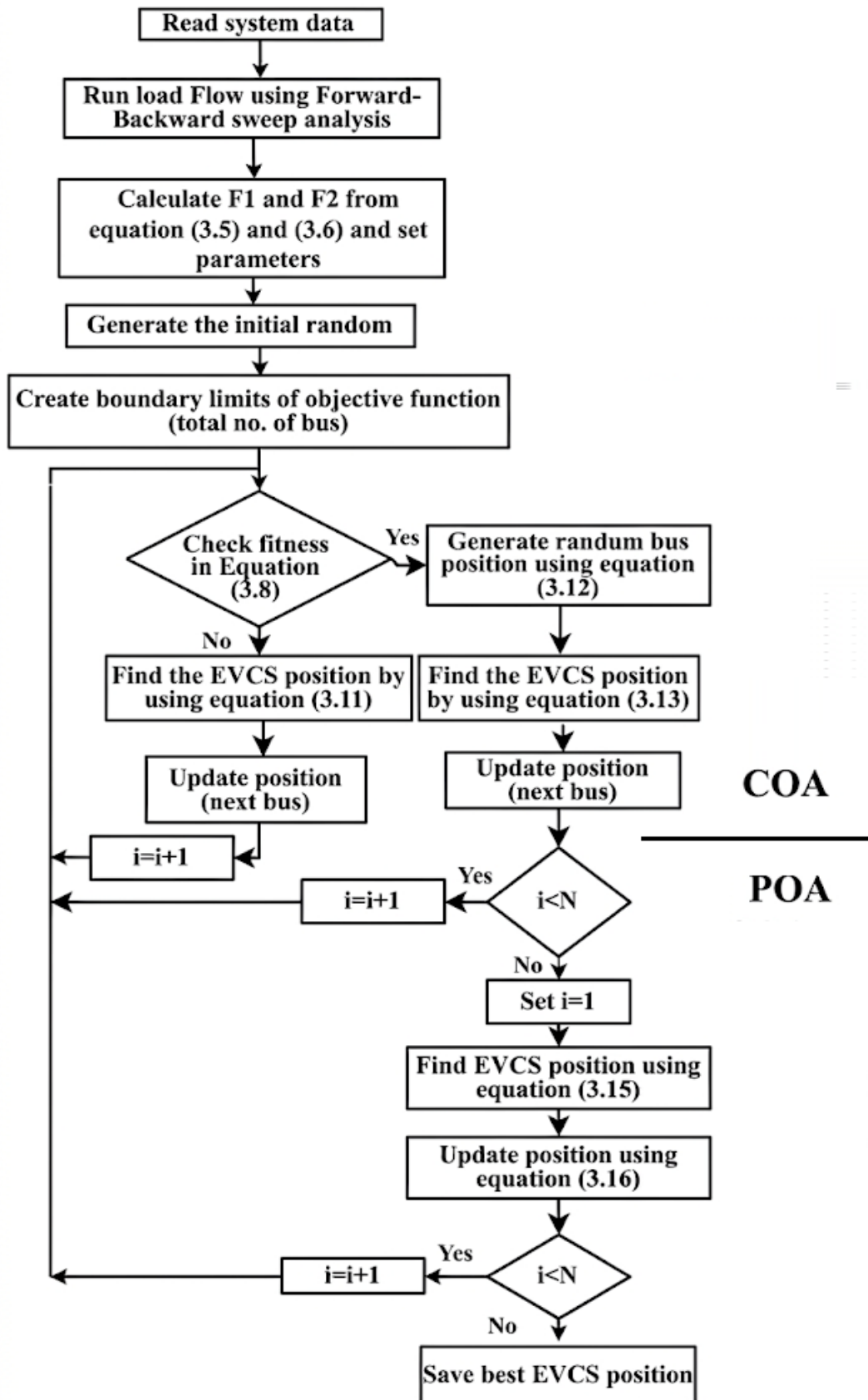


Figure 3. 1 Flowchart for hybrid COA-POA

3.6 Results and Discussion with Random and Optimal EVCS Placement

The MATLAB/Simulink platform is used to implement the proposed method. The findings are obtained for voltage profiles based on EV charging demand. Additionally, individual pelican optimization algorithm (POA), coati optimization algorithm (COA) and hybrid coati and pelican algorithm (COA-POA) convergence plots are used for the comparison analysis. The simulation parameters of EVCS and for hybrid COA- POA method that were used to carry out this proposed work are presented in Table 3.1.

Table 3.1 Simulation Parameter for EVCS and hybrid optimization method

Description	Parameters	Values
EVCS	Rating of charging station	770kW
	Power rating of each charging point	22kW
	Number of charging point	35
	Rated capacity	103Ah
Parameter for hybrid COA- POA method	Input Parameter: population size	33 (for IEEE-33 bus system)
	Boundary limits: Upper	33
	Lower	1
	No. of iteration	100
	Output Parameter	best EVCS location, enhanced voltage stability.

The Hybrid COA-POA algorithms are used in this work to allocate EV charging stations in the best possible way. By considering voltage deviation and voltage stability index, this approach will choose bus 27 for the optimal location of the EV charging station in the IEEE 33 bus distribution system as shown in Figure 3.2. The results are compared with optimal EVCS location on 27th bus with randomly connected EVCS at bus 32 and bus 18 respectively which is also shown in Figure 3.2.

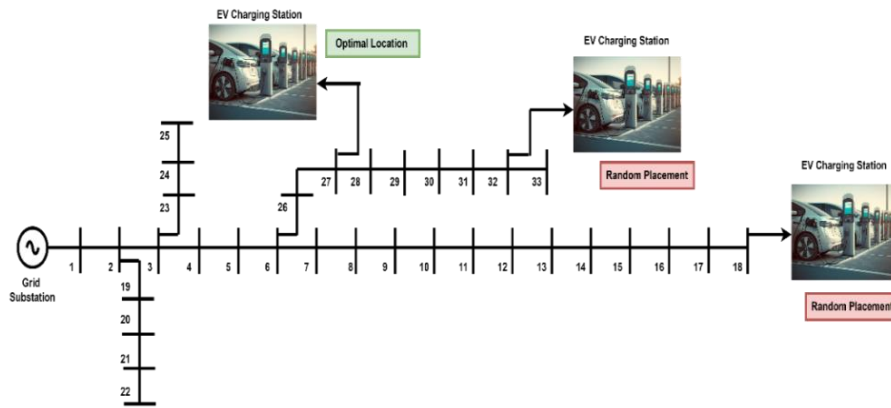


Figure 3.2 IEEE 33 distribution network with optimal & random EVCS placement

For this study, an EV charging station is acting as a load. Nissan Leaf EV's are taken into consideration for charging at charging stations with level 2 charger [145] as given in Table 3.2.

Table 3. 2 EV Battery Specification

Battery parameters	Nissan leaf
Battery capacity	36kWh
Nominal voltage	350V
Energy consumption	21kWh/100km
Power reserve to full charge	175km
Full charge cycle (220V) hour	8h

As EVCS has a power capacity of 770 kW, a maximum of 35 EVs can be charged at EVCS. Whenever EV load power exceeds its rated capacity, the grid will supply the excess power to EV. The results of IEEE 33- bus system is validated considering 3 cases listed below.

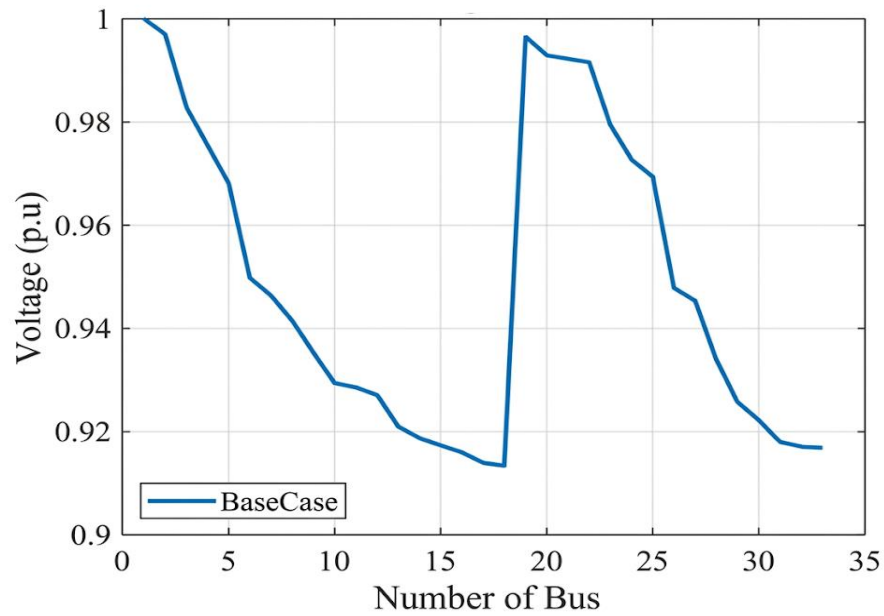
Case 1: Base case,

Case 2: System with random EVCS placement, and

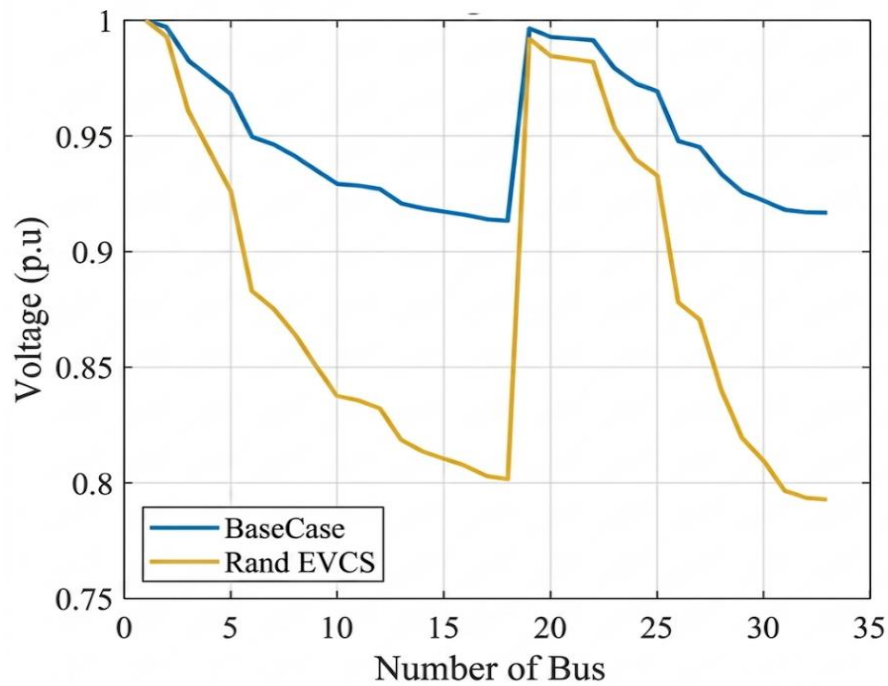
Case 3: System with Optimal EVCS location

Figure 3.3 illustrates the voltage profile of the 33-bus system for the different cases listed above. As the charging load increases, the voltage at each bus keeps dropping. Active and reactive power losses in distribution system affect the voltages on each bus. The system is subject to a total real and reactive demand of 3715kW and 2300kVar. After applying the forward-backward approach to execute the distribution power flow algorithm, bus18 shows

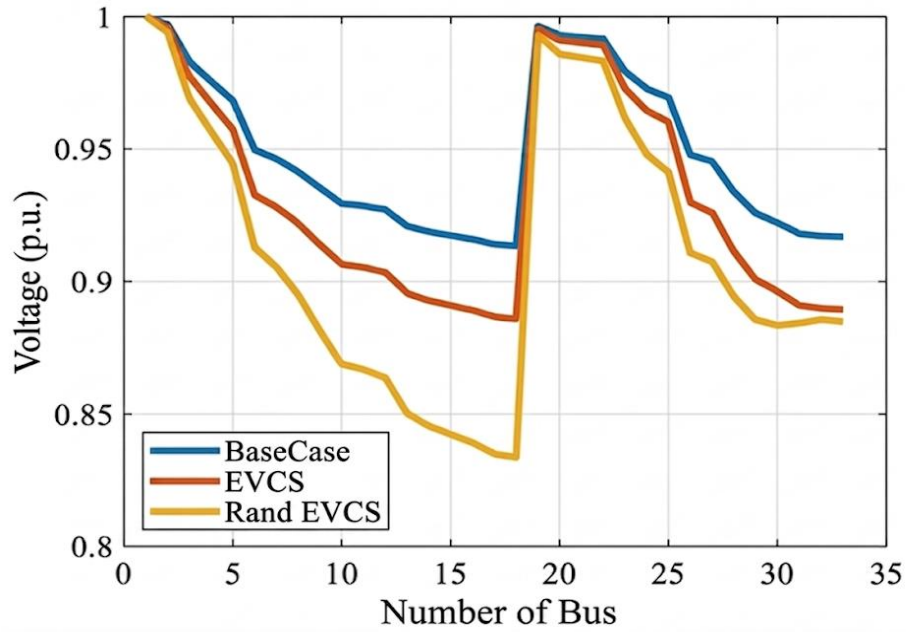
a minimum voltage of 0.9133p.u at base case shown in Figure 3.3 (a). After connecting EVCS at bus 18 and 32 randomly the voltage reduces to 0.8387 p.u. shown in Figure 3.3 (b). However, when EVCS connected at optimal location i.e at bus 27, the voltage at weak bus increases to 0.8857 pu as shown in Figure 3.3 (c).



(a)



(b)



(c)

Figure 3.3: Voltage Profile (a) base case (b) with random EVCS location (c) with optimal EVCS location

The active and reactive power losses for three cases are shown in Figure 3.4 and Figure 3.5 respectively. In addition, the system's total power loss is 242.6703 kW for base case, its increases to 674.08 kW for random EVCS placement and it reduces to 340.3056 kW while placing EVCS optimally shown in Figure 3.6, which shows the efficacy of the method proposed.

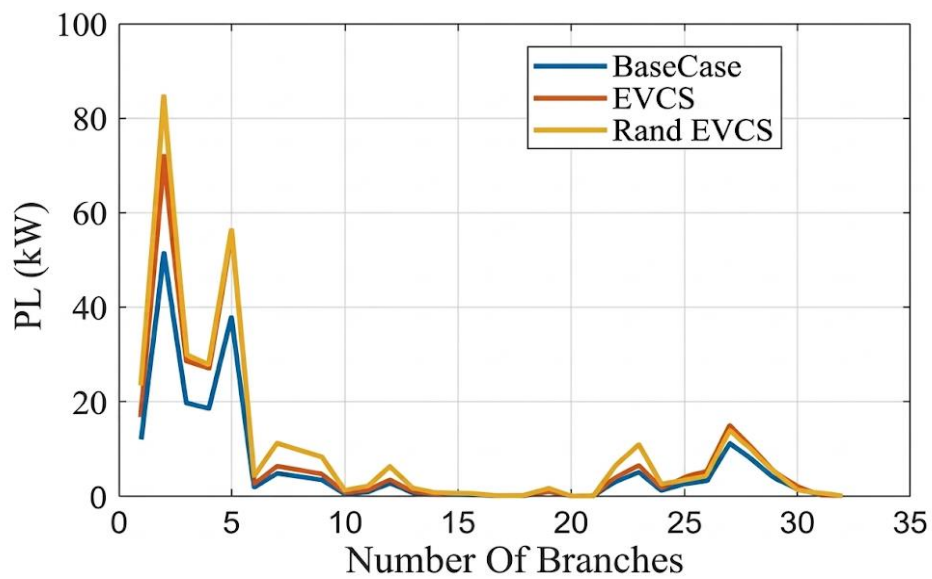


Figure 3. 4 Active power loss

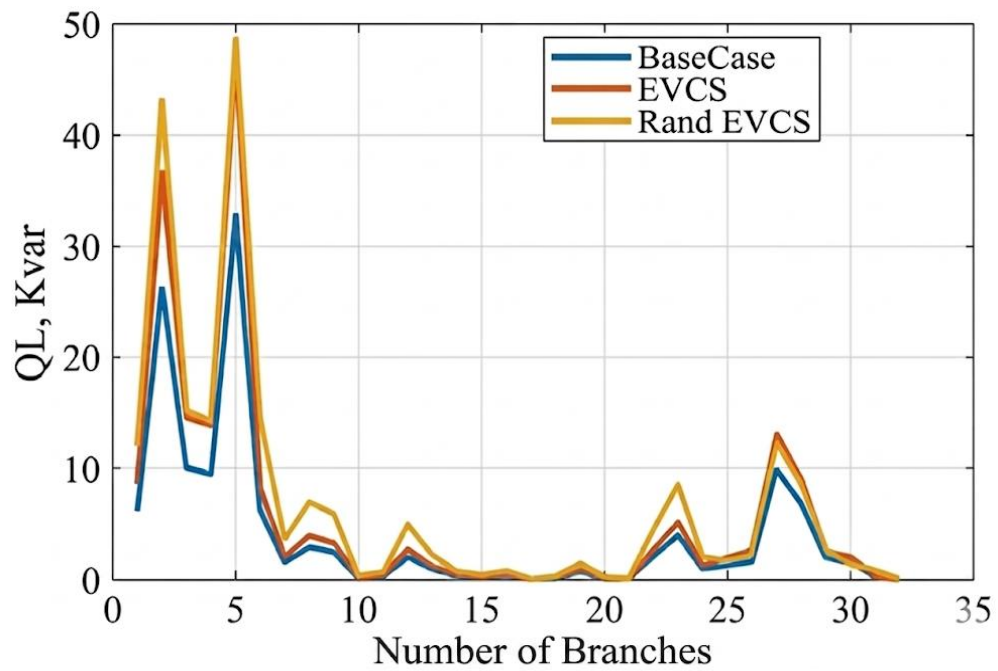


Figure 3. 5 Reactive power loss

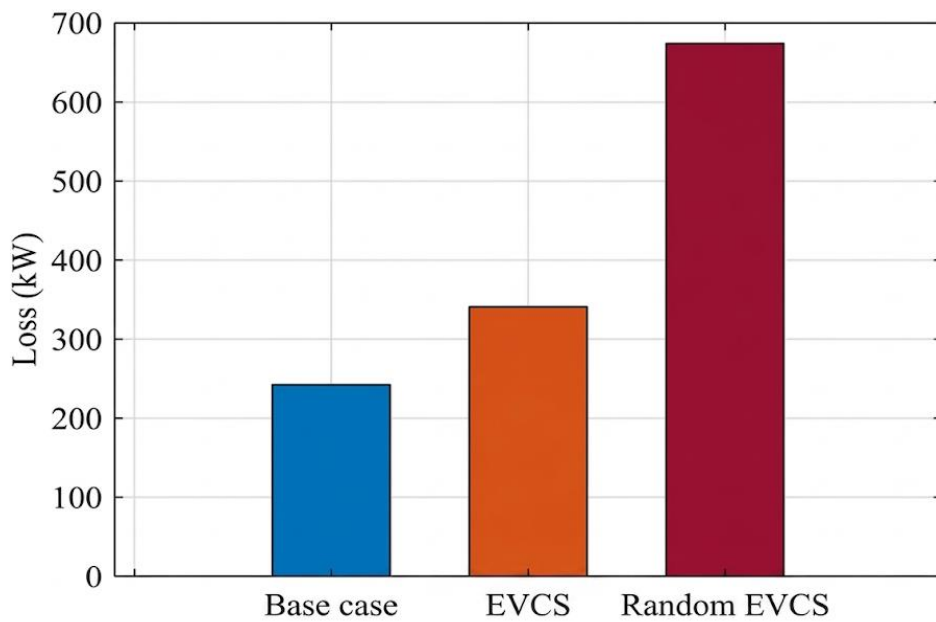


Figure 3. 6 Total Power loss

In Table 3.3, the performance of the IEEE 33-bus distribution system is evaluated under three different scenarios: base case, random EVCS placement, and optimal EVCS placement. The comparison is based on voltage profile, voltage deviation index (VDI), voltage stability index (VSI), and total power losses.

Table 3. 3 Comparative analysis

System	Cases	Total P (load) kW	Total Q (load) kvar	Voltage (p.u) @ bus 18 (33 bus)	Voltage deviation index (VDI)	Voltage stability index (VSI)	Total power Loss (kW)
33-bus	Base case	3715	2300	0.9133	0.05023	0.66716	242.6703
	Random EVCS at bus 18 and bus 32	5255	2300	0.8387	0.05224	0.23486	674.0801
	Optimal EVCS at bus 27	4485	2300	0.8857	0.05082	0.43820	340.3056

In the base case, the system operates under normal loading conditions with a total active power demand of 3715 kW. The voltage at bus 18 is 0.9133 p.u., which is within acceptable limits, and the system shows moderate stability with a VSI of 0.66716. The total power loss is relatively low at 242.67 kW, indicating efficient operation.

When EV charging stations (EVCS) are randomly placed at buses 18 and 32, the total load increases significantly to 5255 kW, leading to system stress. This results in a substantial voltage drop to 0.8387 p.u. at bus 18, which is below acceptable limits. The VSI decreases sharply to 0.23486, indicating poor voltage stability and a higher risk of voltage collapse. Additionally, the power losses increase drastically to 674.08 kW, demonstrating inefficient system performance due to improper placement of EVCS.

In contrast, with optimal placement of EVCS at bus 27, the system performance improves considerably. Although the load increases to 4485 kW, the voltage at bus 18 is maintained at 0.8857 p.u., which is significantly better than the random case. The VSI improves to 0.43820, indicating enhanced voltage stability. Furthermore, the total power loss reduces to 340.31 kW, which is much lower than the random placement scenario. The VDI also shows improvement, reflecting a more uniform voltage profile across the system.

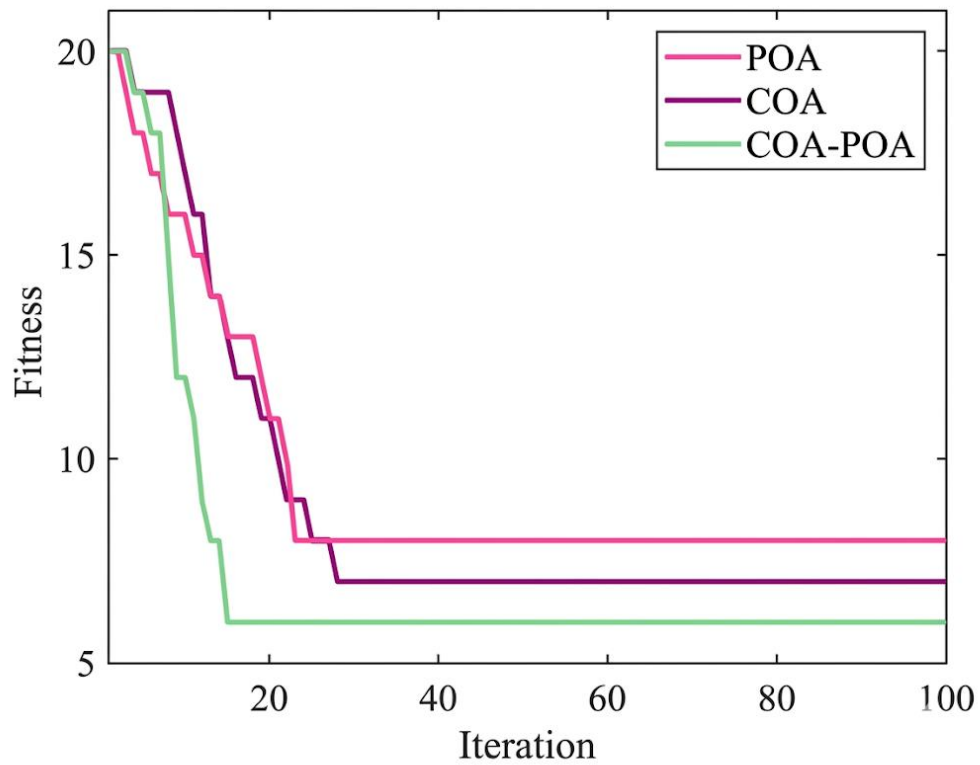


Figure 3. 7 Convergence comparison of proposed hybrid algorithm

Figure 3.7 illustrates the convergence comparison of the proposed hybrid COA-POA algorithm with the individual COA and POA techniques. The convergence curves demonstrate that the hybrid approach attains a stable optimum in significantly fewer iterations, highlighting its superior convergence efficiency. Unlike single optimization algorithms, which are often prone to premature convergence or inadequate exploration, the proposed hybrid method effectively balances global exploration and local exploitation. By integrating COA's strong global search capability with POA's efficient local refinement, the COA-POA algorithm enhances solution diversity, avoids premature convergence, and accelerates convergence speed. The observed fitness convergence confirms the robustness and effectiveness of the proposed optimization framework.

Optimal placement of EVCS significantly enhances system performance by reducing power losses, improving voltage profile, and increasing voltage stability, compared to random placement, thereby ensuring efficient and reliable operation of the distribution system.

3.7 Summary

This chapter presented a hybrid Coati Optimization-Pelican Optimization Algorithm (COA-POA) for the optimal placement of EV charging stations (EVCS) in the IEEE 33-bus distribution system, considering voltage deviation and voltage stability index (VSI) as objective functions. The hybrid technique effectively balances exploration and exploitation, leading to faster convergence and improved solution accuracy.

The results demonstrate that optimal EVCS placement significantly enhances system performance. The voltage deviation index (VDI) at the weakest bus (Bus 18) is reduced from 0.05224 to 0.05082, while the VSI improves from 0.23486 to 0.4382. Moreover, feeder power losses decrease substantially from 674.0801 kW to 340.3056 kW, and all bus voltages remain within acceptable limits even under high EV penetration. Compared to random placement, the proposed method shows superior capability in improving voltage profile, enhancing stability, and minimizing losses.

Despite these improvements, increasing EV penetration continues to impose additional stress on the distribution network. To address this challenge, the next chapter focuses on the optimal integration of solar PV and wind generation using the World Cup Optimization (WCO) algorithm, aiming to provide localized voltage support, further reduce losses, and enhance overall voltage stability.

Chapter- 4

OPTIMAL DG PLACEMENT FOR VOLTAGE STABILITY ENHANCEMENT

This chapter focuses on the optimal placement of distributed generation (DG) units for enhancing voltage stability in distribution systems using the World Cup Optimization (WCO) algorithm. With increasing load demand and high penetration of electric vehicle charging stations (EVCS), maintaining an acceptable voltage profile and system stability has become a critical challenge.

To address these issues, a multi-objective optimization framework is developed considering Fast Voltage Stability Index (FVSI), Line Stability Index (LSI), and Loss Sensitivity Factor (LSF) as key performance indicators. These indices enable accurate identification of weak buses and critical lines, ensuring effective DG allocation for improved voltage support and reduced system losses.

The proposed WCO-based approach aims to determine the optimal size and location of DG units such that voltage deviation is minimized, system losses are reduced, and overall voltage stability is enhanced. The effectiveness of the method is validated on a standard IEEE distribution test system under various operating conditions, demonstrating its superiority in achieving reliable and stable system performance.

4.1 Introduction

The global imperative to reduce carbon emissions has accelerated the integration of photovoltaic (PV) based distributed generation (DG) into power distribution networks. However, uncoordinated DG placement can adversely affect system performance, including voltage instability and power losses. This study uses the World Cup Optimization (WCO) algorithm to propose an efficient methodology for distributed generation (DG) deployment, validated on the IEEE 33-bus radial distribution system. The aim is to curtail total real power losses and enhance voltage stability by identifying optimal locations for PV and wind-based DG units. WCO, a metaheuristic technique inspired by the dynamics of international football

tournaments, has shown promise in various optimization contexts but remains underutilized in DG planning. This study explores its potential to address DG placement as a global optimization problem. The performance of the distribution system is initially analysed without DGs using a forward-backward sweep power flow method. Subsequently, WCO is employed to determine the optimal DG locations, and the results are benchmarked against those obtained using Particle Swarm Optimization (PSO), a well-established technique in power system optimization. Comparative analyses are conducted based on power loss reduction, voltage profile improvement, convergence behaviour, and computational efficiency. The MATLAB/Simulink simulation results validate that WCO outperforms PSO in terms of convergence speed and solution quality. The findings demonstrate that WCO is a robust and computationally efficient tool for placement of DG, offering a novel and effective approach to enhancing distribution system performance.

4.2 Problem Statement-2

- Voltage Stability Assessment: Post-EVCS allocation, Voltage Stability Index (VSI) analysis identifies critical buses exhibiting voltage vulnerability during peak demand periods.
- Distributed generation (DG) sources are incorporated with EVCS to lessen the impact of EV charging load.
- Charging stations are combined with DG units, increases the motivation to use EVs.
- As the current CSs are fossil fuels based and causing environmental issues which affects the human health through the emission of various gases such as SO_x, NO_x, and carbon monoxides particularly in metropolitan cities of India.
- Thus, the solar PV and wind based CSs will not only reduce the burden on the existing electrical networks but also provides the sustainable, cost effective and eco-friendly environment. In this regard, the feasibility studies of solar PV and wind-based CS are a new research area.

4.3 Proposed Methodology for Problem Statement-2

✓ RES Optimal Siting Using World Cup Optimization (WCO)

- Multi-Objective WCO Application: World Cup Optimization algorithm simultaneously optimizes PV and wind unit locations to maximize VSI margins

while minimizing network losses.

- Key Features: WCO's tournament-based exploration-exploitation balance ensures global optima for hybrid RES configurations.

4.4 Solar and Wind Modelling

In this work, solar and wind turbine are used as an input source for EV charging station. A solar photovoltaic cell (PV) utilizes the photovoltaic effect to convert its solar energy from sunlight into electrical power. Most often used type of solar cells are silicon ones. Temperature and sun radiation are two examples of physical and environmental elements that have a significant impact on photovoltaic system efficiency. Solar irradiation and PV power output terminal current are almost exactly equivalent. The power generated from PV panel is evaluated using below equation;

$$P_{pv}(t) = A\eta\mu(t) \quad (4.1)$$

Where, $P_{pv}(t)$ indicates PV power, A denotes area of solar panel placement, η specifies PV panel's efficiency and $\mu(t)$ represent irradiance of solar. Wind turbine converts wind energy into electrical energy, in this work doubly fed induction generator (DFIG) wind turbine model is used. Wind turbine generated power is calculated using below equation;

$$P_{wind}(t) = 0.5C_p\rho Av^3 \quad (4.2)$$

Where, $P_{wind}(t)$ denotes power obtained from wind turbine in kW, A indicates area swept by wind turbine in m^2 , C_p power coefficient, ρ signifies air density kg/m^3 and v represent wind velocity in m/s. The integration of EV charging stations may affect the stability of the power system due to fluctuating charging demand. To enhance system stability, solar and wind energy sources are incorporated into the charging infrastructure. The optimal placement of these distributed generation sources is determined using the World Cup Optimization (WCO) algorithm.

4.5 World Cup Optimization Algorithm

This optimization algorithm used for improving line stability index, FVSI and line stability factor in this work. This WCO [182] is inspired from FIFA world cup match to obtain title as an optimal solution. A mathematical model of the team competition process is used to

evaluate global optimal solution. In this work, solar and wind are placed in optimal location of IEEE 33 bus system using this WCO. The WCO method starts with a random population to find the global optimal point. The basic flow chart is shown in Figure 4.1.

The structure and development of teams in a football World Cup tournament serve as the model for the World Cup Optimization (WCO) algorithm, a population-based optimization method. Initialization of teams is the first step in the process, where a collection of potential solutions (teams/countries) are formed at random. The performance of each team is then assessed using a fitness function, which establishes the quality of the solution for the given challenge.

Teams are then divided into various pools, much like during a World Cup group stage. Teams compete within each category, and the results are compared. The top-performing teams group winners and runners-up are chosen to move on to the next phase based on this assessment. To preserve diversity, underperforming teams may be disbanded or replaced with fresh applicants. After that, the algorithm moves on to the knockout phase, when chosen teams compete in a series of rounds. Teams might "learn" from more formidable rivals during this phase when solutions are further refined through techniques like combination, mutation, or local search. The population steadily improves as weaker answers are eliminated and better ones develop in this ongoing iterative competition.

When a stopping criterion such as reaching a maximum number of iterations or obtaining a good fitness value is satisfied, the process comes to an end. The ideal or nearly ideal solution to the issue is represented by the top team still standing at the end of the competition.

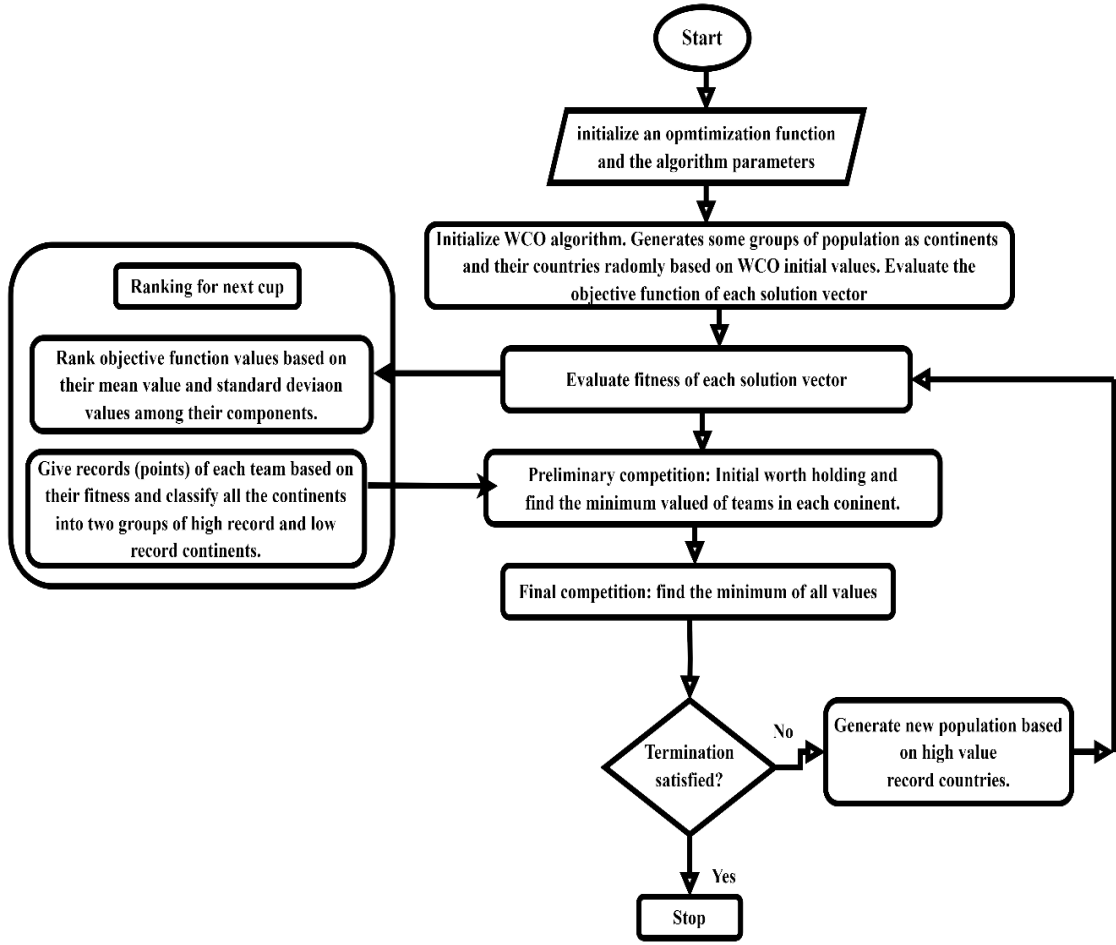


Figure 4.1 Basic Flowchart of WCO Algorithm [182]

Let N indicates variable dimensions (buses) and m denotes total iterations.

$$W = \begin{bmatrix} W_{1,1} & W_{2,1} & \cdots & W_{m,1} \\ W_{1,2} & W_{2,2} & \cdots & W_{m,2} \\ \vdots & \vdots & \ddots & \vdots \\ W_{i,N} & W_{j,N} & \cdots & W_{m,N} \end{bmatrix} \quad (4.3)$$

The matrix W represents the population structure used in the World Cup Optimization (WCO) algorithm. $W_{i,j}$ represents the value of the j^{th} optimization variable for the i^{th} candidate solution. In this matrix, each row corresponds to a candidate solution, while each column represents an optimization variable. The WCO algorithm is a population-based metaheuristic optimization technique inspired by the competition strategy of FIFA World Cup tournaments.

Objective function of WCO algorithm is considered as follows;

$$F = F_r(W_{i,N}, W_{j,N}, \dots, W_{m,N}) \quad (4.4)$$

Where, F is objective or fitness value of the candidate solution, F_r represent fitness evaluation function.

The WCO algorithm is formulated with the aim of improving the Line Stability Index (LSI), Fast Voltage Stability Index (FVSI), and Line Stability Factor (LSF). Accordingly, the objective function adopted for the proposed method is given as follows:

A line with has a higher stability value is closer to instability. Root discriminant of the voltage quadratic equation is set to zero to obtain real roots of voltage. Line is at a critical state if index is close to unity. In order to maintain a safe state, index needs to be lower than 1.

The equation for line stability index is as follows;

$$F_1 = \frac{4XQ_R}{Q_R \sin(\alpha - \beta)^2} \quad (4.5)$$

Line stability factor must be maintained below 1 to obtain optimal stability of the system. It can evaluate as follows;

$$F_2 = \frac{4X}{V_S^2} \left[\frac{XP_S^2}{V_S^2} + Q_R \right] \quad (4.6)$$

Fast voltage stability should be near to one, if is not in this value, it causes instability.

$$F_3 = \frac{4ZQ_R}{V_S^2 X} \quad (4.7)$$

Considering voltage magnitude of all the buses must be within the allowed upper and lower limits. The network's operating system constraints.

$$\begin{aligned} V_{\min} &\leq V \leq V_{\max} \\ V_{\min} &= 0.95 p.u. \text{ \& } V_{\max} = 1.05 p.u. \end{aligned} \quad (4.8)$$

Where, X indicates inductive reactance, Q_R denotes reactive power, V_S represent sending end voltage, α denotes angle at sending end, β indicates angle at receiving end, P_S signifies active power at sending end and Z denotes line impedance and $V_{\min}$ \& $V_{\max}$

denoted the minimum and maximum voltage limits.

The final objective function of the proposed optimization approach is formulated as the maximization of the combined effect of the three indices, namely the LSI, FVSI, and LSF. Therefore, the overall objective function is expressed as:

$$F = \text{Max}(F_1 + F_2 + F_3) \quad (4.9)$$

"Rank" is a crucial parameter in the WCO method. Rank significantly affects the solution. Upon acquiring rank scores, the top 'n' teams are placed in first seed, the next 'n' inferior teams in second seed, and other teams are categorized in a hierarchical manner similar to the first and second seeds. The ranking of the obtained fitness value is set as follows;

$$R = \frac{\chi \times \sigma + \bar{W}}{2} \quad (4.10)$$

$$\bar{W} = \frac{1}{n} \sum_{i=1}^n W_i \quad (4.11)$$

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (W_i - \bar{W})^2} \quad (4.12)$$

Where, R indicates ranking, χ denotes increasing or decreasing values, σ represent standard deviation, w_i population value, $\bar{W}$ specifies mean value and n indicates number of population. In this WCO method, second best value is evaluated immediately after evaluating the first iterations. Updating the position for next iteration is done using below equation;

$$W_{new} = [W_{best}, W_{Rand}] \quad (4.13)$$

Where, w_{new} denotes new population matrix, w_{best} indicates best obtained value and w_{Rand} represent random value. w_{best} is obtained as follows;

$$\left(\frac{1}{2} \times A(u-l) \right) < W_{best} < \left(\frac{1}{2} \times A(u+l) \right) \quad (4.14)$$

Where, A signifies accuracy parameter, u denotes upper bound and l represent lower bound. This process will continue till the best values obtained. The flowchart for WCO algorithm for optimal placement of DG is shown in Figure 4.2. The WCO optimally select the bus for PV and wind based on fitness function used in this algorithm. The parameters

and the total number of repetitions are randomly initialized, and each parameter's fitness function is estimated. If the limit is reached, change the limit between the optimum ranges and update the position of a parameter. Iteration is repeated till obtaining optimal position for allocation.

This optimal allocation will enhance the stability of the distributed system. Figure 4.3 indicates the proposed modified IEEE 33 distributed bus system with optimal EVCS, PV and Wind location.

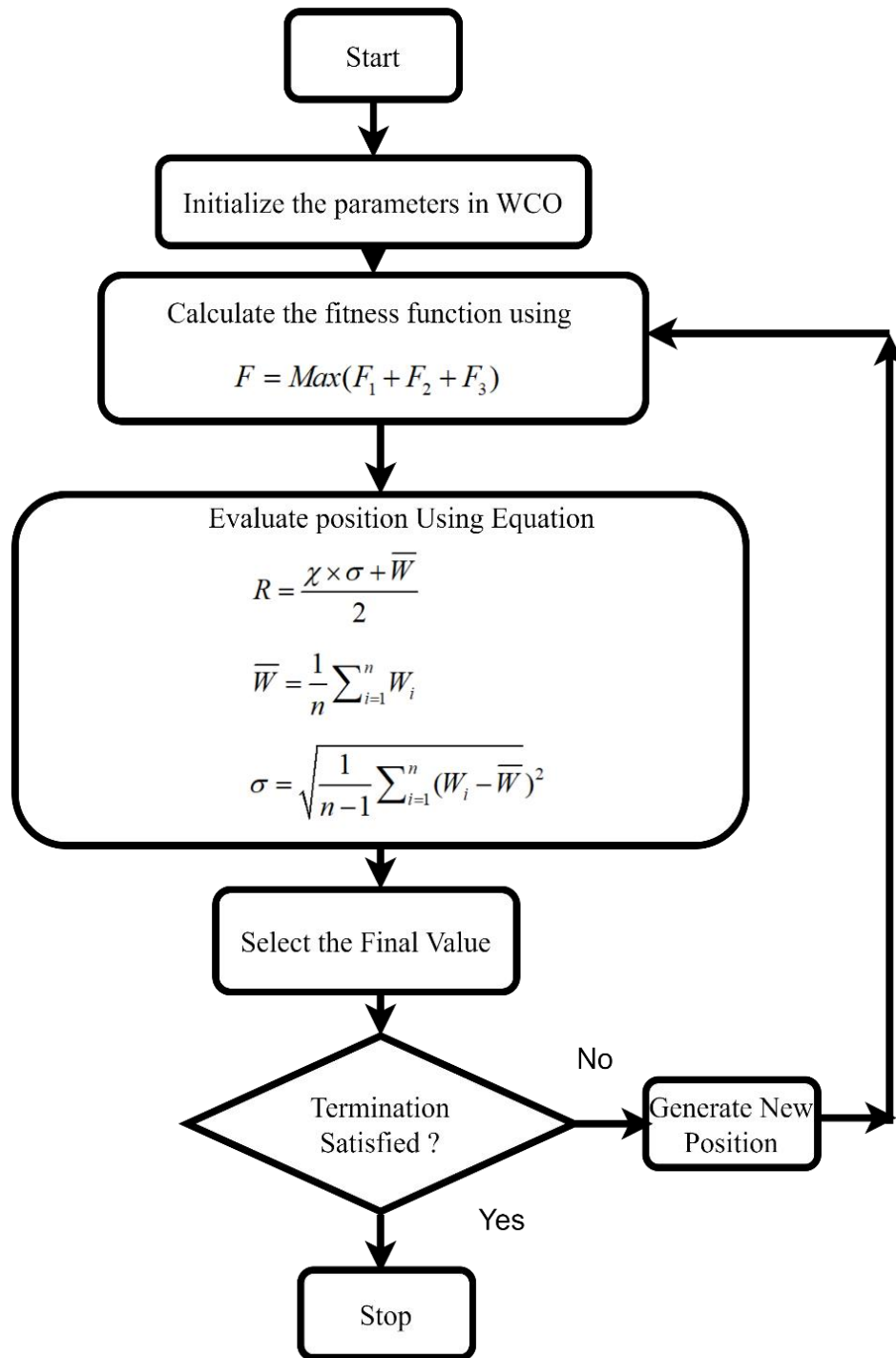


Figure 4.2 Flowchart for WCO algorithm for optimal placement of DG

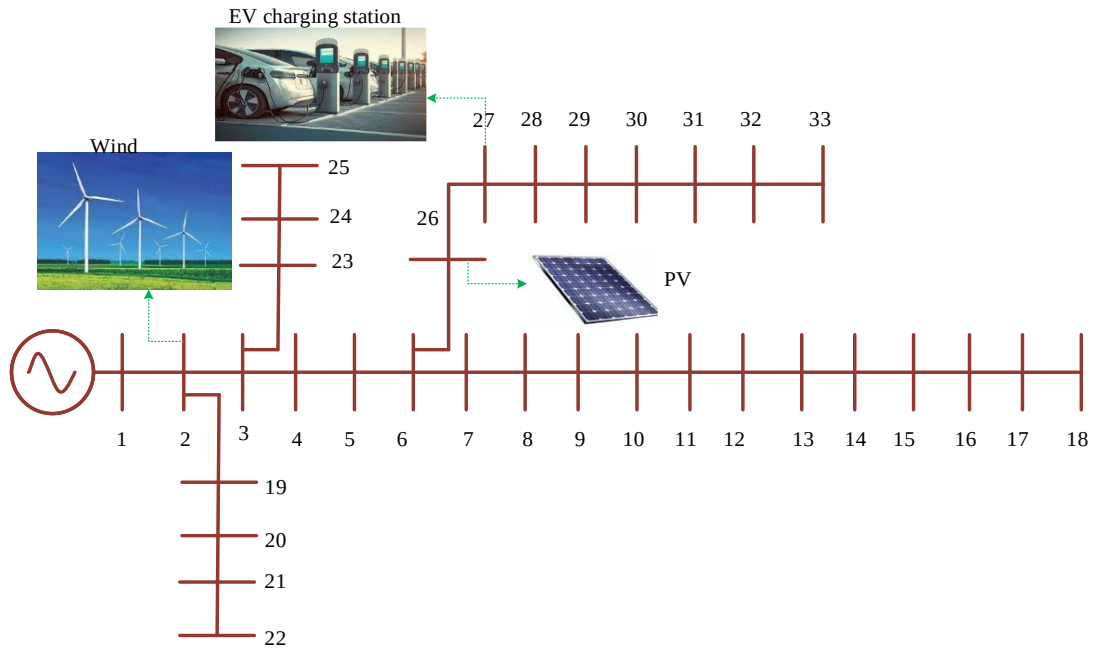


Figure 4.3 IEEE 33 distribution network with optimal EVCS, PV and Wind

In this work IEEE 33 distribution network is employed for evaluation of voltage stability of charging station. Placing the EV charging station may cause instability, thus to enhance the voltage stability, WCO method is used to place PV and wind sources.

4.6 Results with Random EVCS, Optimal EVCS and PV Placement

4.6.1 The results of IEEE 33 bus distribution system with optimal PV placement

The results of random placement of EVCS and optimal placement of EVCS and PV in IEEE 33 bus distribution system are validated considering 4 cases listed below.

Case 1: Base case

Case 2: System with random EVCS placement

Case 3: System with Optimal EVCS

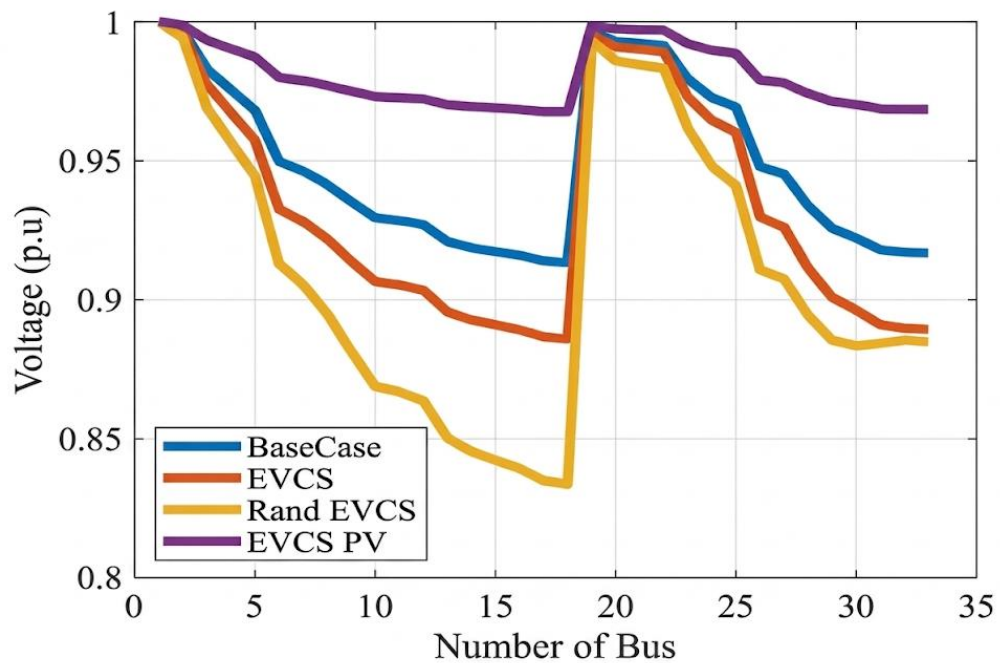
Case 4: System with optimal EVCS & PV placement

The solar PV and wind parameter used for implementation is shown in Table 4.1 below. The solar and wind output power rating is 775 kW and 1MW respectively.

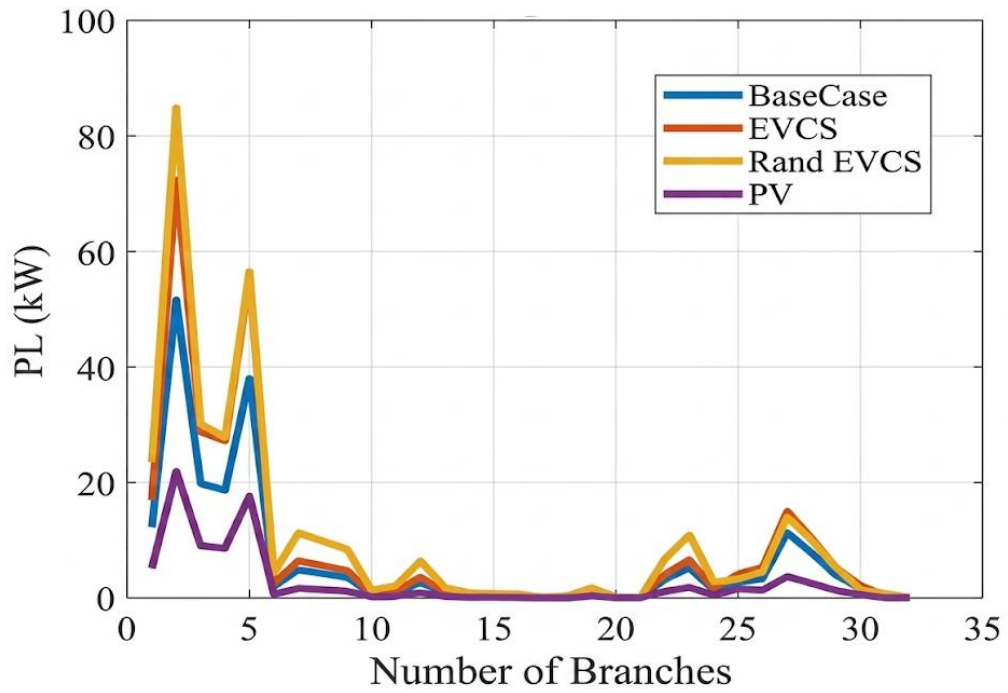
Table 4.1 PV and wind parameter specification

PV	Power	775kW
	Terminal Voltage of Solar Module	350 V
	Current output of solar module	5.58 A
	Parallel string	318
	Series Connected modules per string	8
	Module specific cells	96
	Open circuit voltage (Voc)	54.74 V
	Short Circuit Current (Isc)	5.58 A
Wind	Nominal Power	1MW
	Frequency	50 hz

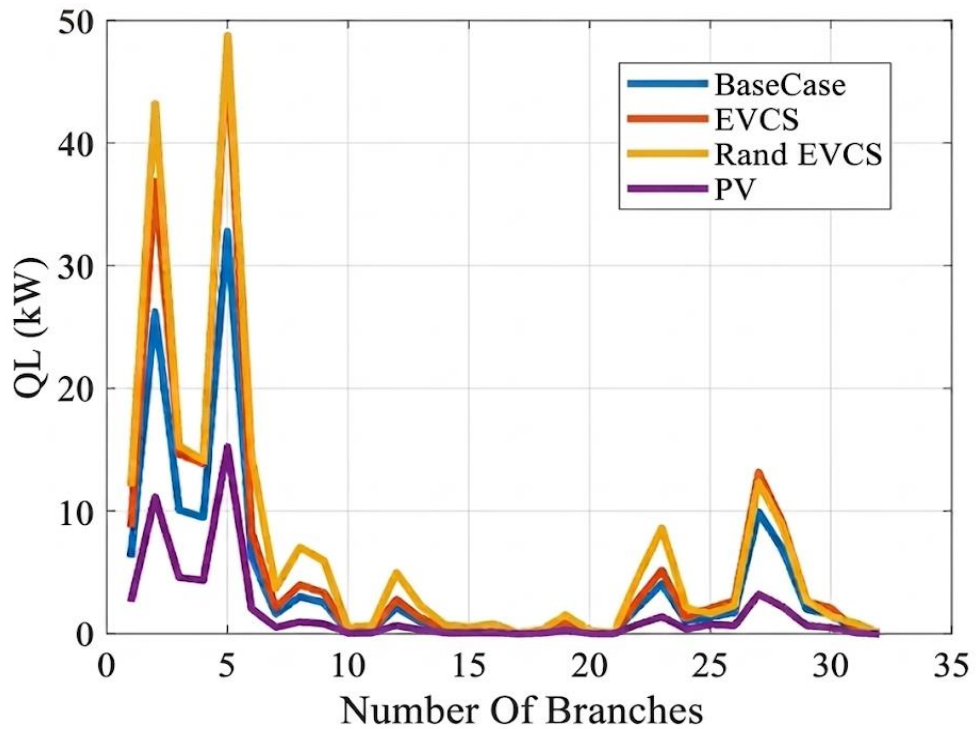
The Voltage stability is further improved by connecting renewable sources in the system. Here solar PV is connected at bus 26. It has been observed that after placing Solar PV, the voltage profile is further improved and losses are further reduced to 99.47 kW as shown in Figure 4.4 (a), (b) and (c) respectively. Further, various VSI's are calculated and compared.



(a)



(b)

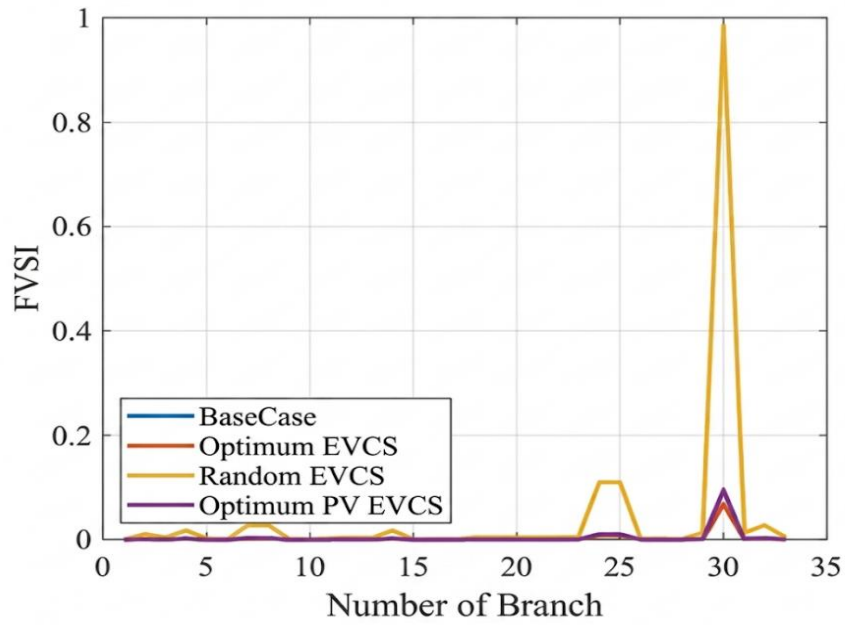


(c)

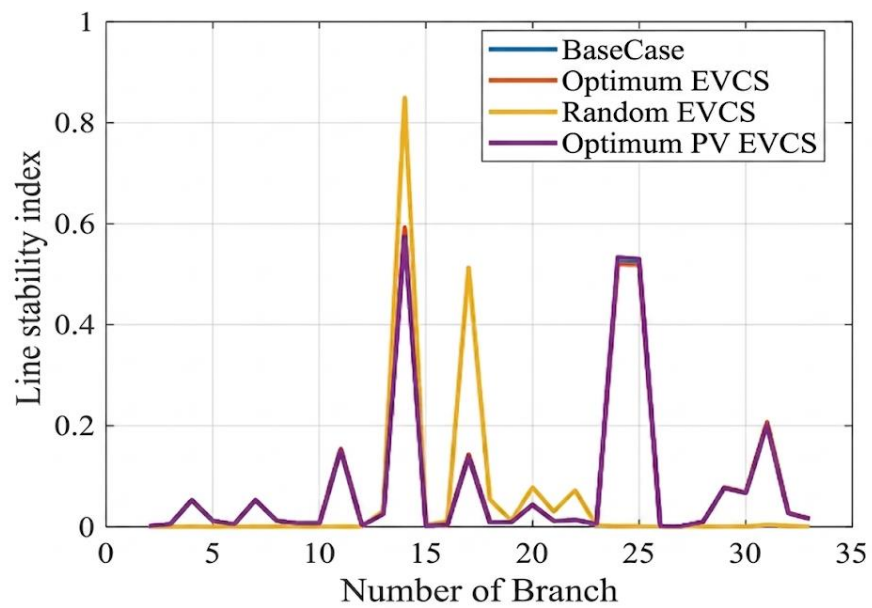
Figure 4. 4 (a) Voltage profile (b) Active power loss and (c) reactive power loss

Figure 4.5 (a), (b) and (c) illustrates the variation of the FVSI, LSI and LSF across all buses of the IEEE 33-bus radial distribution system under four operating scenarios, namely the

base case, optimal EVCS placement, random EVCS placement, and combined PV-EVCS integration. It has been observed that the index values remain significantly below unity for most buses in the base case, confirming stable voltage operation under normal loading conditions. However, under random EVCS placement, a sharp rise in FVSI is observed near the tail-end buses around bus 30, LSI at 14 and LSF around bus 18, with the index approaching unity, indicating the system's proximity to voltage instability. After placing EVCS and PV optimally the index values significantly enhance below unity at all the busses.



(a)



(b)

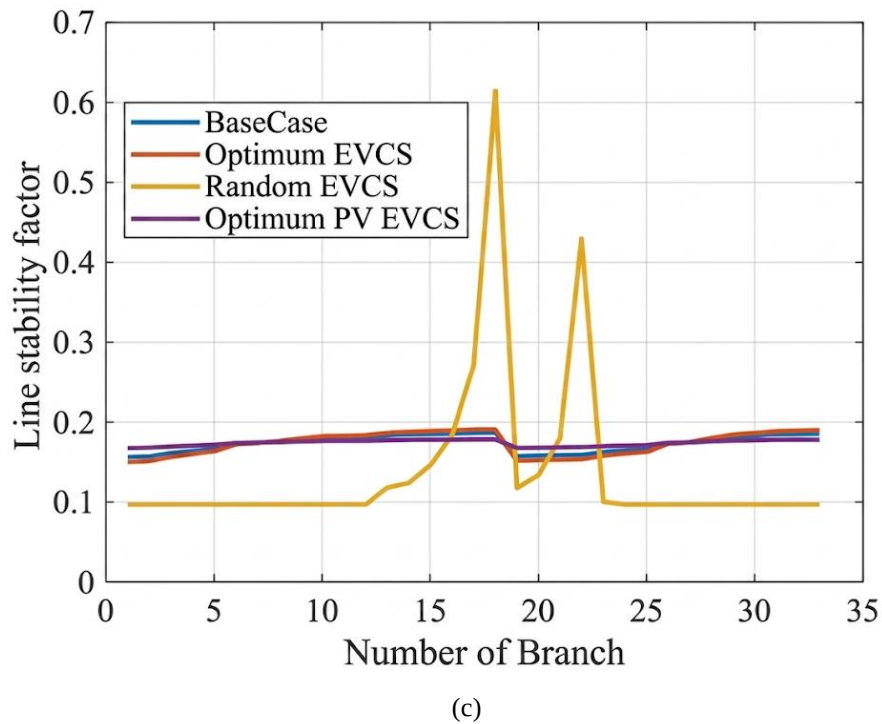


Figure 4.5 VSI's for 33 IEEE system (a) Line Stability Factor (b) Fast Voltage Stability Index (c) Line Stability Index

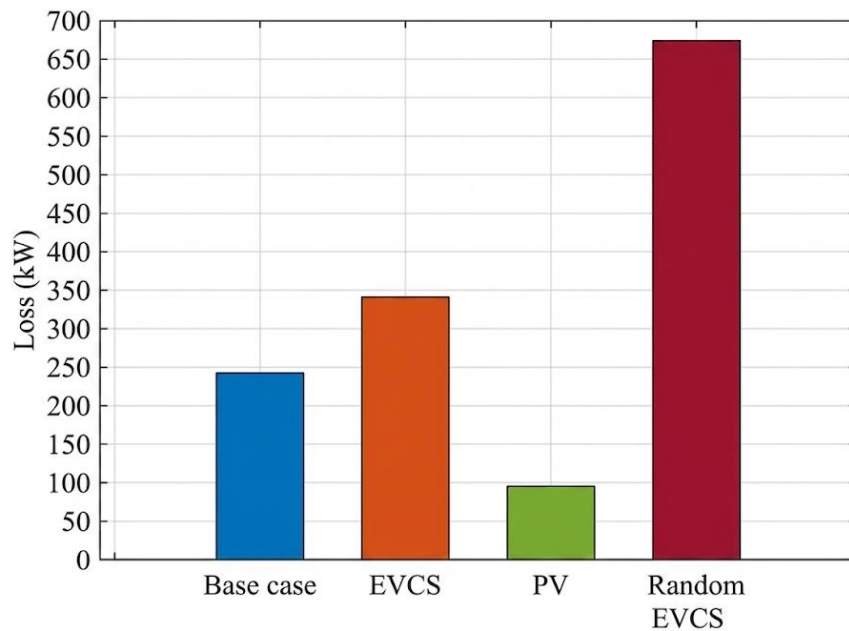


Figure 4.5 Comparison of total losses for IEEE 33 bus system

The comparison of total losses is shown in Figure 4.5 which clearly shows that optimally placing EVCS with solar PV generation gives reduced losses against base case and random placement.

4.6.2 Validation using IEEE-69 bus Radial Distribution System

The effectiveness of the proposed algorithm is further validated using the IEEE 69-bus distribution system. The IEEE 69-bus test system is illustrated in Figure 4.6, which indicates the locations of randomly placed and optimally placed EV charging stations (EVCS) along with the PV array integration. The system is experiencing a total real and reactive demand of 3801.4 kW and 2693.6 kVAr. Bus 65 has the most voltage deviation and the worst of all the buses. At bus number 65, the voltage is 0.9102 p.u. The system's total reactive power loss is 102.1647 kVAr, while its total active power loss is 224.8807 kW.

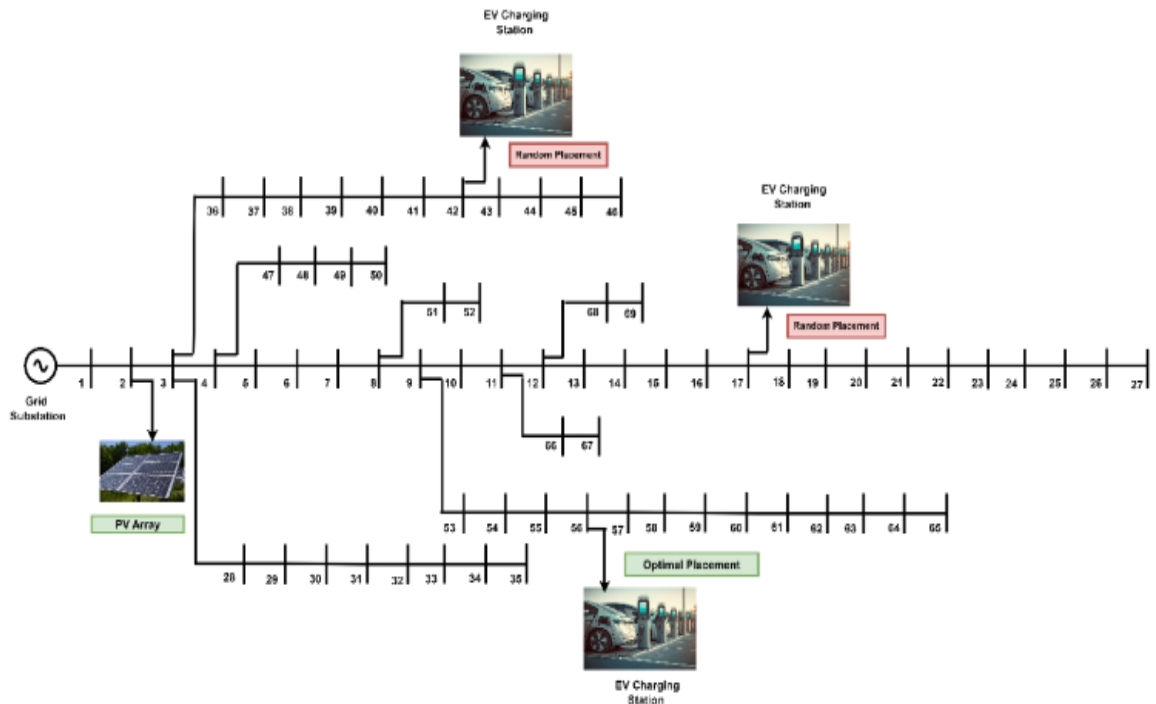


Figure 4.6 IEEE 69 bus distribution network with random and optimal EVCS and PV

Figure 4.7 illustrates the voltage profile of the IEEE 69-bus distribution system under different operating conditions, namely the Base Case, EVCS, Random EVCS, and EVCS with PV integration. The voltage magnitude at each bus is represented in per-unit (p.u.) values along the distribution feeder.

In the Base Case, the voltage profile remains within acceptable limits with a moderate voltage drop toward the end buses. When Electric Vehicle Charging Stations (EVCS) are integrated, the additional charging demand increases power consumption, leading to a further reduction in bus voltages. The voltage drop becomes more severe in the Random

EVCS case because of the uncoordinated placement and charging of EV loads, which causes higher stress on specific sections of the distribution network.

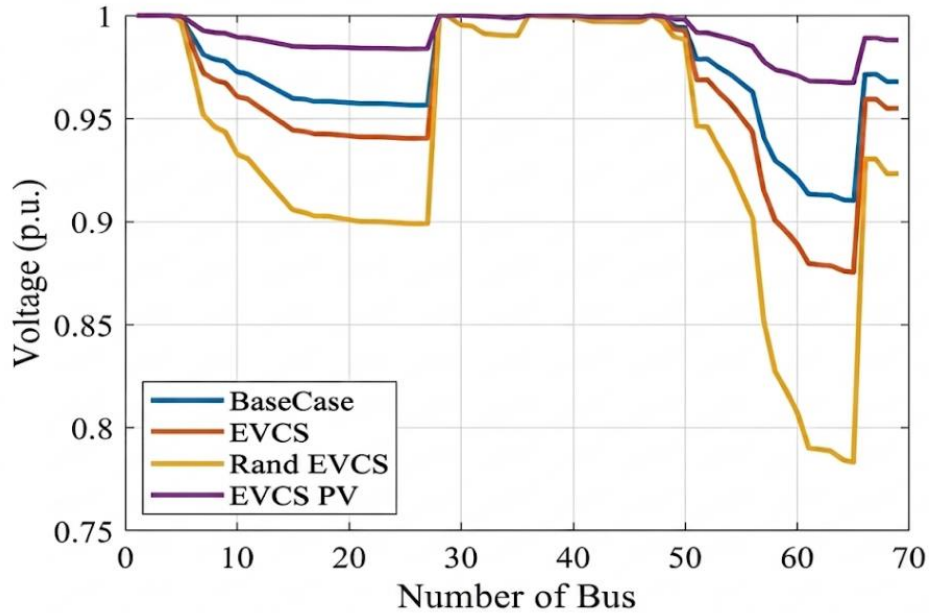


Figure 4.7 Voltage profile of IEEE 69 bus for various cases

On the other hand, the EVCS PV case shows significant improvement in the voltage profile compared to the other cases. The integration of photovoltaic (PV) generation near the charging stations provides local power support, thereby reducing feeder loading and minimizing voltage drops. As a result, the bus voltages remain closer to the nominal value of 1 p.u. throughout the system.

Overall, the figure demonstrates that increasing EV charging load adversely affects the voltage profile of the distribution system, whereas the incorporation of PV generation effectively enhances voltage regulation and system performance.

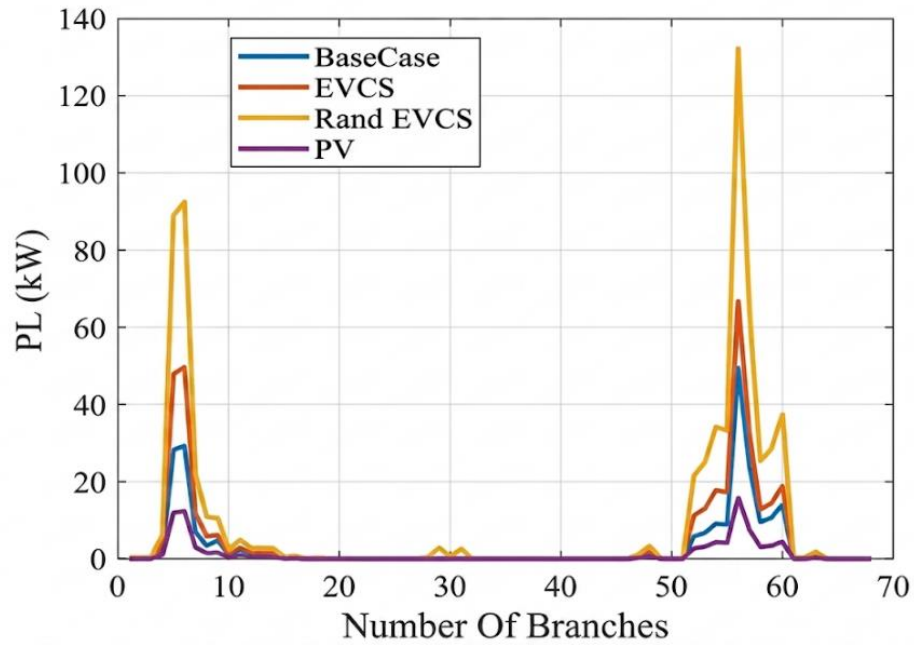


Figure 4.8 Active power loss of IEEE 69 bus for various cases

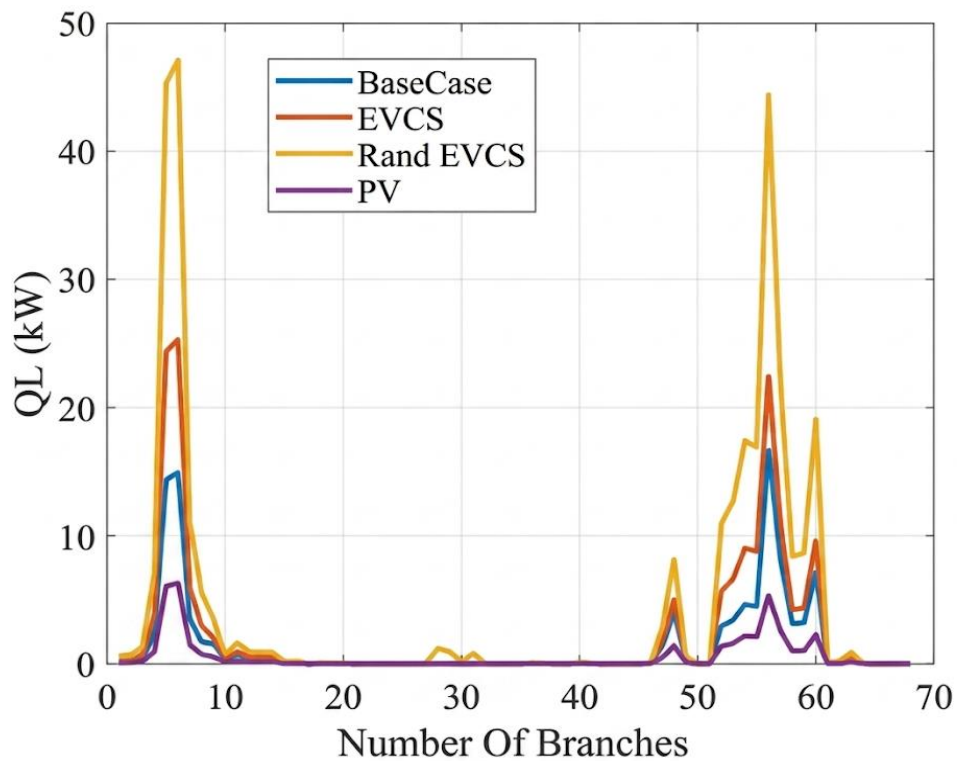


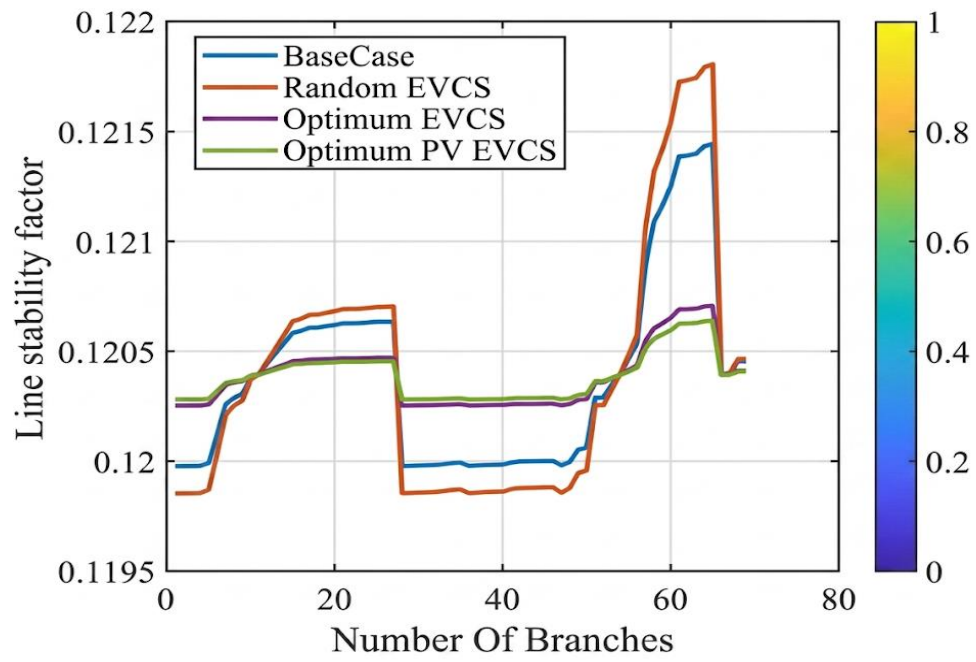
Figure 4.9 Reactive power loss of IEEE 69 bus for various cases

The active and reactive power loss for each branch is shown in Figure 4.8 and 4.9 respectively. These losses are calculated for all the cases and obtained from IEEE 69

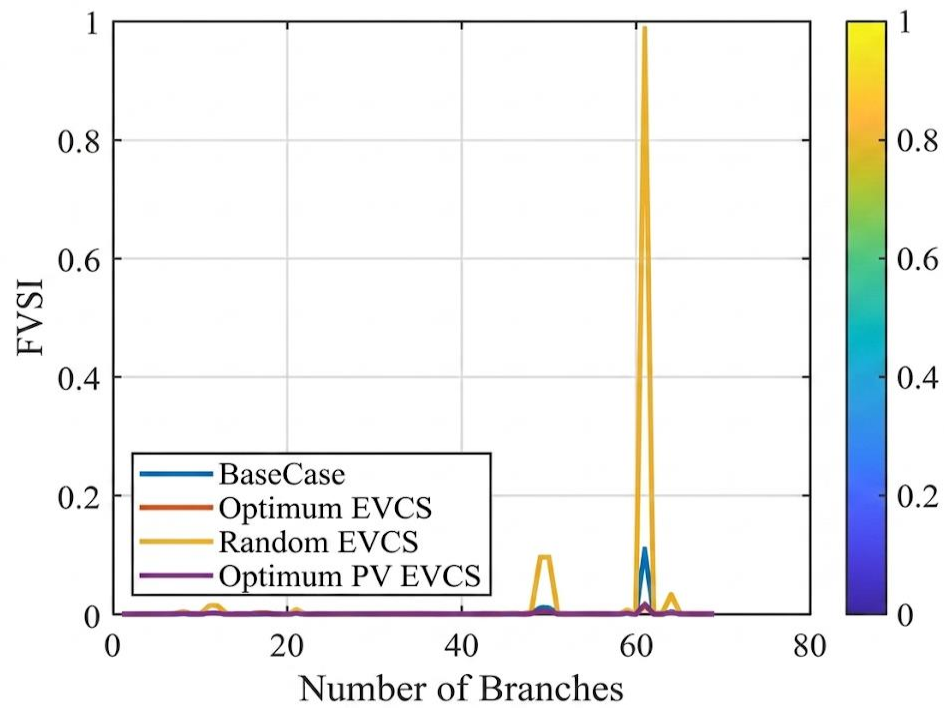
distributed system. It has been observed that after optimally placing the EVCS on 56 bus using hybrid coati and pelican optimization algorithm by considering voltage deviation and stability as fitness, the voltage profile has been improved and power loss is reduced at each bus. For random EVCS allocation on bus 17 and 52, the total power loss is 616.7783 kW and for optimal placement of EVCS gives 323.2390 kW. Voltage stability is further enhanced by integrating renewable sources into the system. In this case, a solar PV is connected at bus 2. It has been observed that after placing Solar PV the voltage profile is improved and losses can be further reduced to 79.3011 kW.

Further various VSI's are calculated and compared. Figure 4.10 a, b and c illustrates the variation of the LSF, FVSI and LSI respectively across all buses of the IEEE 69-bus radial distribution system under four operating scenarios, namely the base case, optimal EVCS placement, random EVCS placement, and combined PV-EVCS integration. It is observed that the FVSI values remain significantly below unity for most buses in the base case, confirming stable voltage operation under normal loading conditions. However, under random EVCS placement, a sharp rise in FVSI is observed near the tail-end buses (around bus 61), with the index approaching unity, indicating the system's proximity to voltage instability.

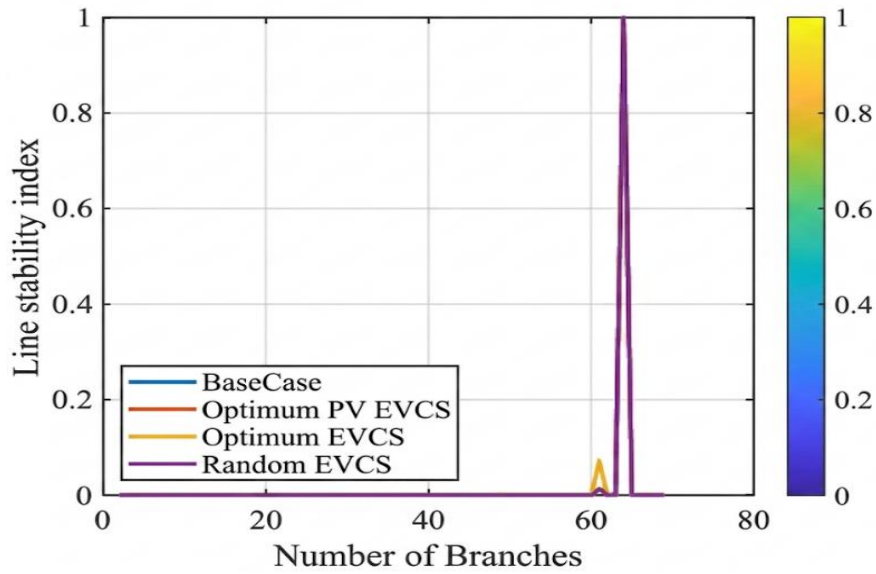
In contrast, the proposed optimal EVCS placement strategy results in substantially reduced FVSI values across all buses, demonstrating improved voltage stability margins. Furthermore, the integration of optimally placed PV units along with EVCS leads to an additional reduction in FVSI, highlighting the beneficial impact of distributed renewable generation in mitigating voltage stress. The results clearly establish that unplanned EVCS penetration can severely weaken voltage stability, whereas coordinated EVCS and RES placement significantly enhances the system's stability margin and prevents potential voltage collapse conditions.



(a)



(b)



(c)

Figure 4. 10 VSI's for 69 bus IEEE system (a) Line Stability Factor (b) Fast Voltage Stability Index (c) Line Stability Index

The comparison of total active loss is shown in Figure 4.11 which clearly shows that optimally placing EVCS with solar PV generation gives reduced losses against base case and random placement.

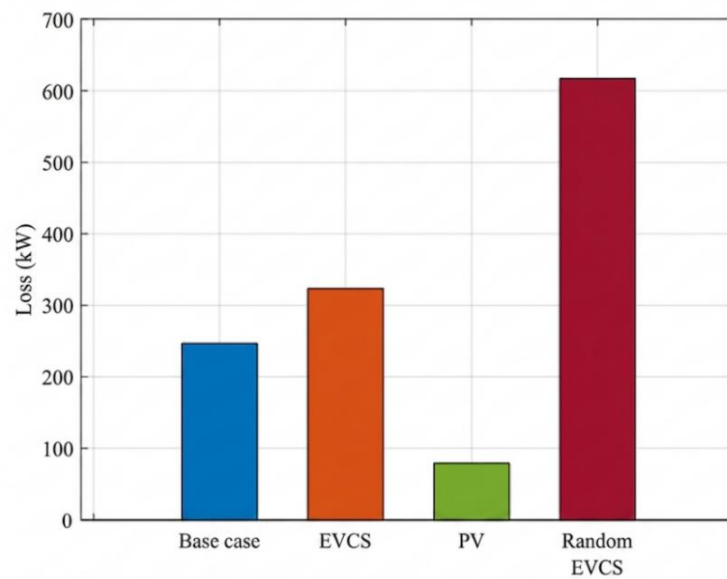


Figure 4.11 Comparison of total losses

The comparative analysis concerning total active load, reactive load, bus voltage variation, various stability indices and total power loss for IEEE 33 and 69 bus system is shown in Table 4.2.

Table 4.2 Comparative analysis of IEEE 33 and 69 bus system performance

System	Cases	Total P (load) kW	Total Q (load) kvar	Voltage (p.u) @ bus 18 (33 bus) and @ bus 65 (69 bus)	FVSI	LSI	LSF	Total power Loss (kW)
33-bus	Base case	3715	2300	0.9133	0.000302	0.000208	0.06547	242.6703
	Random EVCS at bus 18 and bus 32	5255	2300	0.8387	0.000419	0.001288	0.35515	674.0801
	optimal EVCS at bus 27	4485	2300	0.8857	0.000328	0.000437	0.074547	340.3056
	With optimal EVCS & solar PV	4485	2300	0.9681	0.000156	0.000125	0.054547	99.47897
69-bus	Base case	3801.4	2693.6	0.9102	0.000417	0.000191	0.0136	246.6144
	Random EVCS at bus 17 and bus 52	5341.4	2693.6	0.8025	0.002210	0.001951	0.1204	616.7783
	optimal EVCS at bus 56	4571.4	2693.6	0.8982	0.000528	0.000195	0.01218	323.2390
	With optimal EVCS & solar PV	4571.4	2693.6	0.9695	0.000380	0.000123	0.0124	79.3011

Above table represent the analysis of performance of the distribution system under four scenarios: base case, random EVCS placement, optimal EVCS placement, and optimal EVCS integrated with solar PV. The evaluation is based on voltage profile, Fast Voltage Stability Index (FVSI), Line Stability Index (LSI), Line Stability Factor (LSF), and total power losses.

For IEEE 33 Bus system, in the base case, the system operates with a load of 3715 kW, maintaining a voltage of 0.9133 p.u. at bus 18, which is within acceptable limits. The stability indices (FVSI = 0.000302, LSI = 0.000208, LSF = 0.06547) indicate a stable operating condition, with total power loss of 242.67 kW.

With random EVCS placement at buses 18 and 32, the load increases significantly to 5255 kW, causing system stress. The voltage drops sharply to 0.8387 p.u., indicating poor voltage regulation. The stability indices (FVSI, LSI, LSF) increase considerably, reflecting proximity to voltage instability. The power loss rises drastically to 674.08 kW, confirming inefficient and stressed operation.

For 69 bus system, In the case of optimal EVCS placement at bus 27, the system performance improves notably. The voltage at bus 18 increases to 0.8857 p.u., and the stability indices reduce compared to the random case (FVSI = 0.000328, LSI = 0.000437, LSF = 0.074547), indicating improved stability margins. The total power loss is significantly reduced to 340.31 kW.

When solar PV is integrated with optimally placed EVCS, the system shows the best performance. The voltage rises to 0.9681 p.u., close to the nominal value. The stability indices reach their lowest values (FVSI = 0.000156, LSI = 0.000125, LSF = 0.054547), indicating a highly stable system. Additionally, the power loss is minimized to 99.48 kW, demonstrating the effectiveness of DG support in improving system efficiency and voltage stability.

For the base case, with a load of 3801.4 kW, the voltage at bus 65 is 0.9102 p.u., and stability indices are low (FVSI = 0.000417, LSI = 0.000191, LSF = 0.0136), indicating stable operation. The total power loss is 246.61 kW.

With random EVCS placement at buses 17 and 52, the load increases to 5341.4 kW, resulting in a severe voltage drop to 0.8025 p.u., which is below acceptable limits. The stability indices increase significantly (FVSI = 0.002210, LSI = 0.001951, LSF = 0.1204), indicating high risk of voltage instability. The power loss increases to 616.78 kW, reflecting poor system performance.

In the optimal EVCS placement at bus 56, system conditions improve. The voltage increases to 0.8982 p.u., and stability indices are reduced (FVSI = 0.000528, LSI = 0.000195, LSF = 0.01218), showing improved voltage stability. The total power loss decreases to 323.24 kW.

With optimal EVCS integrated with solar PV, the system achieves the best results. The voltage rises significantly to 0.9695 p.u., and stability indices further decrease (FVSI = 0.000380, LSI = 0.000123, LSF = 0.0124), indicating enhanced stability margins. The power loss is minimized to 79.30 kW, confirming improved efficiency and reduced stress on the network. Overall,

- Random EVCS placement leads to severe voltage drops, higher losses, and poor stability.
- Optimal EVCS placement significantly improves voltage profile and reduces losses.
- Integration of solar PV with optimally placed EVCS provides the best performance by, enhancing voltage profile, minimizing stability indices and by reducing power losses drastically.

Thus, coordinated planning of EVCS and renewable DG is essential for maintaining stability and efficiency in modern distribution systems.

In Table 4.3, several optimization methods' performance in reducing active power loss (APL) and enhancing voltage profiles in a 33-bus system are compared. Hybrid Coati and Pelican optimization (HCOA-PAO) is a suggested technique that reduces power losses and improves voltage stability more effectively than other algorithms like Genetic Algorithm (GA), Harmony search algorithm (HSA), Hybrid Grey Wolf optimization (GWO), Particle Swarm Optimization (PSO), and Cuckoo Search optimization (HGP_CS).

Table 4. 3 Comparative outcomes of the suggested approach with references to relevant literature

System	Method [Ref.No.]	Active power loss (kW)	Vmin (p.u)
33-bus	Genetic Algorithm (GA) [152]	141.60	0.9290
	Harmony search Algorithm (HSA) [153]	138.06	0.9342
	Hybrid GWO, PSO, and Cuckoo Search optimization (HGP_CS) [154]	134.77	0.9588
	Hybrid Coati and Pelican optimization (HCOA-PAO) (Proposed)	99.47	0.9681
69-bus	Gray wolf optimization (GWO) [158]	85.92	0.9302
	Particle Swarm Optimization (PSO) [158]	87.56	0.9453
	Hybrid Coati and Pelican optimization (HCOA-PAO) (Proposed)	79.30	0.9695

4.6.3 Results and Discussion with EVCS, PV and with Varying Load Condition

In this research, the study of various VSIs is demonstrated for five various cases. They are mentioned below.

Case 1: Base case

Case 2: Optimum placement of DG using WCO

Case 3: Optimum placement of DG using PSO

Case 4: System load of 125% of the base case

Case 5: System load of 150% of the base case

It has been found that when solar PV is positioned optimally, losses are decreased and the voltage profile is enhanced. Figure 4.12 displays the voltage profile for each of the aforementioned cases, which indicates the improvement in voltage profile from 0.913374 p.u without DG to 0.935246 p.u. with optimal DG location using the WCO method compared to the remaining cases.

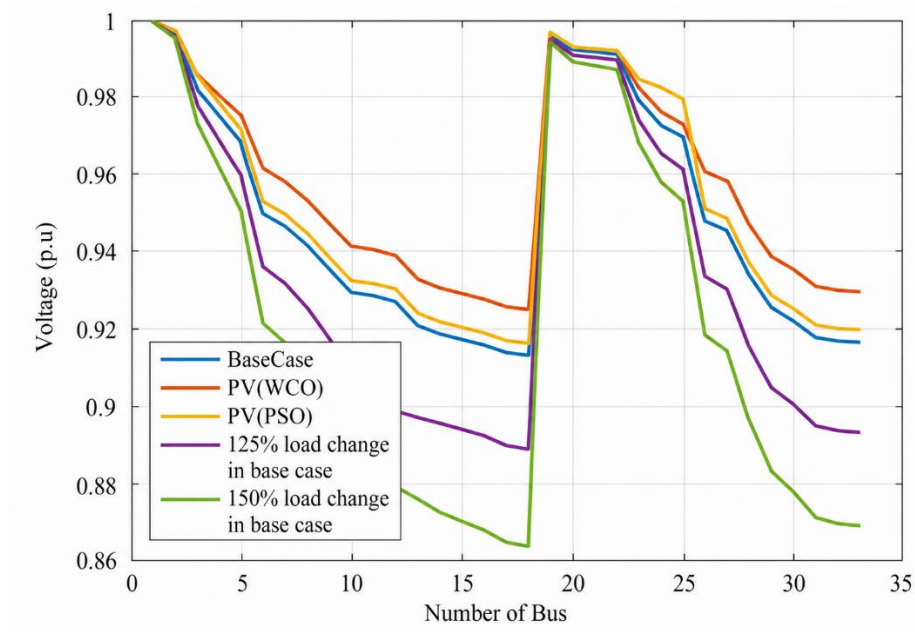


Figure 4.12 Voltage Profile

The comparison of reactive power loss and active power loss is shown in Figure 4.13 and Figure 4.14 respectively which shows that DG using the WCO approach compared to the other methods, yields the lowest active and reactive losses. Further various VSI's are calculated for various cases listed above and compared.

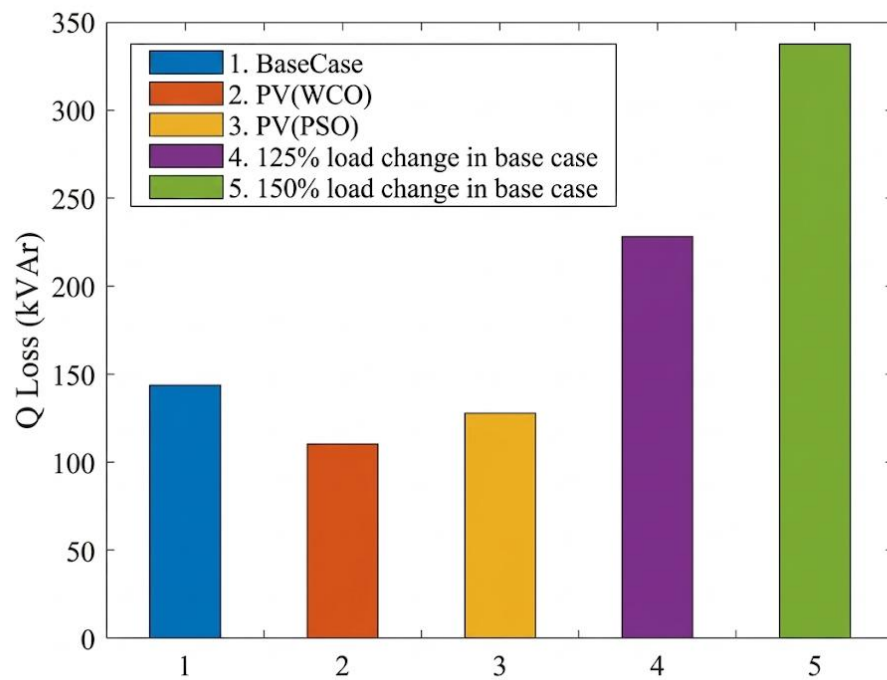


Figure 4. 13 Comparison of reactive power loss

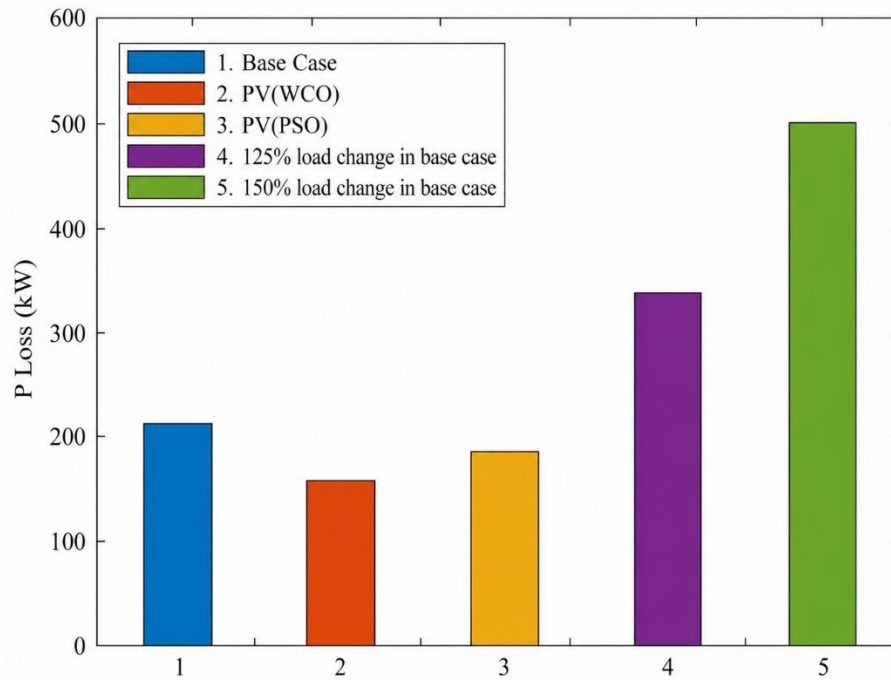


Figure 4. 14 Comparison of active power loss

Table 4.4 shows the voltage profile, losses, and VSIs for base case loading. The voltage at bus 18 is 0.913374 p.u., while the reactive and active power losses are 0.306941 kVAR and 0.337403 kW, respectively. The FVSI, LSI, and LSF obtained are 0.020177, 0.020177, and 0.001218 respectively.

Table 4.4 Comparative analysis of various VSIs evaluated for base case.

base case							
Line no.	Bus no.	V (p.u)	Ploss (kW)	Qloss (kVar)	FVSI	LSF	LSI
1-2	2	0.997039	12.47697	6.480653	0.003839	0.000719	0.000595
2-3	3	0.982978	51.85543	26.53205	0.014088	0.001591	0.000346
3-4	4	0.975522	20.07770	10.34587	0.021239	0.001622	0.001403
4-5	5	0.968150	18.87738	9.735035	0.00842	0.000458	0.000773
5-6	6	0.949797	38.30995	33.09086	0.010247	0.006356	0.000275
6-7	7	0.946343	2.197378	6.589086	0.021054	0.054703	0.042189
7-8	8	0.941495	5.118476	1.862875	0.075197	0.008107	0.017496
8-9	9	0.935243	4.461632	3.266490	0.013874	0.007403	0.000203
9-10	10	0.929443	3.841841	2.786928	0.014302	0.007589	0.000280
10-11	11	0.928582	0.837373	0.448157	0.006407	0.000393	0.000237

11-12	12	0.927081	1.164521	0.556356	0.014279	0.000228	0.001615
12-13	13	0.920992	2.948057	2.361103	0.034796	0.019187	0.000366
13-14	14	0.918746	1.012856	1.224287	0.029747	0.029510	0.004262
14-15	15	0.917343	0.641156	0.582908	0.003948	0.004032	0.000043
15-16	16	0.915982	0.565620	0.470739	0.010427	0.004372	0.000434
16-17	17	0.913978	0.535783	0.601065	0.017955	0.043729	0.000214
17-18	18	0.913374	0.337403	0.306941	0.020177	0.011023	0.001218
2-19	19	0.996511	0.445251	0.41889	0.003692	0.000592	0.000246
19-20	20	0.992937	1.116458	1.015138	0.034257	0.043850	0.000164
20-21	21	0.992233	0.385056	0.383008	0.009401	0.005514	0.000160
21-22	22	0.991597	0.327933	0.322992	0.016733	0.021117	0.000524
3-23	23	0.979393	3.465501	2.43898	0.014095	0.002434	0.000330
23-24	24	0.972725	5.427501	4.326596	0.108944	0.283197	0.028479
24-25	25	0.969402	1.571631	1.272608	0.109684	0.280660	0.033966
6-26	26	0.94788	2.878308	1.586583	0.003899	0.000144	0.000884
26-27	27	0.945335	3.605356	1.95621	0.005489	0.000281	0.000387
27-28	28	0.933931	11.56092	10.20768	0.013665	0.011835	0.000541
28-29	29	0.925743	8.102288	7.076146	0.037023	0.027631	0.000886
29-30	30	0.922219	4.172425	2.245754	0.247127	0.011067	0.007038
30-31	31	0.918039	1.877123	1.839488	0.045188	0.084072	0.001462
31-32	32	0.917118	0.497385	0.513659	0.020853	0.023425	0.002631
32-33	33	0.916833	0.297462	0.285764	0.009956	0.004160	0.000247

The comparative study for VSIs evaluated for Optimal placement (PSO technique) of PV on the 28th bus is given in Table 4.5. Reactive and active power losses are decreased to 0.306652 kVAR and 0.337035 kW, respectively, at bus 18, while the voltage is enhanced by 0.92456 p.u. The FVSI, LSI, and LSF obtained are 0.020225, 0.012144, and 0.001219 respectively.

Table 4.5 Comparative analysis for VSI'S evaluated for Optimal placement (PSO technique) of PV on 28th bus in IEEE-33 bus system.

Optimal PV placement (PSO)							
Line no.	Bus no.	V (p.u)	Ploss (kW)	Qloss (kVar)	FVSI	LSF	LSI
1-2	2	0.997508	9.192913	4.806567	0.003872	0.000802	0.000599
2-3	3	0.985957	36.61987	18.77212	0.014134	0.001760	0.000347

3-4	4	0.978529	19.94408	10.27782	0.021307	0.001790	0.001405
4-5	5	0.971187	18.75126	9.670803	0.008446	0.000506	0.000771
5-6	6	0.95289	38.05155	32.8678	0.010276	0.007008	0.000276
6-7	7	0.949435	2.184515	6.546565	0.021113	0.060316	0.042237
7-8	8	0.944606	5.085727	1.852052	0.075403	0.008938	0.017415
8-9	9	0.938371	4.433080	3.245977	0.013911	0.00816	0.000203
9-10	10	0.932587	3.817473	2.769656	0.014339	0.008364	0.000280
10-11	11	0.931731	0.833579	0.446903	0.006423	0.000434	0.000238
11-12	12	0.930234	1.158472	0.554356	0.014315	0.000251	0.001616
12-13	13	0.924161	2.929707	2.346666	0.034882	0.021142	0.000367
13-14	14	0.921918	1.007831	1.217673	0.02982	0.032514	0.004265
14-15	15	0.920518	0.638689	0.580712	0.003957	0.004443	0.000418
15-16	16	0.91916	0.563673	0.469317	0.010452	0.004817	0.000435
16-17	17	0.917158	0.53404	0.598739	0.017998	0.048175	0.000214
17-18	18	0.92456	0.337035	0.306652	0.020225	0.012144	0.001219
2-19	19	0.996981	0.445099	0.418745	0.003723	0.000660	0.000248
19-20	20	0.993407	1.115669	1.014428	0.034546	0.048891	0.000165
20-21	21	0.992703	0.384960	0.382897	0.009481	0.006148	0.000162
21-22	22	0.992067	0.327892	0.322937	0.016874	0.023544	0.000528
3-23	23	0.984637	0.946493	0.717769	0.014076	0.002662	0.000329
23-24	24	0.982478	1.240471	1.020334	0.107794	0.217308	0.028131
24-25	25	0.979178	1.546053	1.252594	0.108513	0.301191	0.033548
6-26	26	0.950983	2.860419	1.577471	0.003910	0.000159	0.000885
26-27	27	0.948449	3.582402	1.944524	0.005504	0.000310	0.000387
27-28	28	0.937091	11.48282	10.13882	0.013700	0.013044	0.000542
28-29	29	0.928936	8.048084	7.028925	0.037114	0.030445	0.000887
29-30	30	0.925431	4.145439	2.232008	0.247718	0.012196	0.007033
30-31	31	0.921261	1.865992	1.828487	0.045293	0.092609	0.001463
31-32	32	0.920341	0.495895	0.511922	0.020901	0.025803	0.002632
32-33	33	0.920056	0.297370	0.285621	0.009980	0.004583	0.000244

Table 4.6 shows the comparative study for VSIs evaluated for optimal placement (WCO technique) of PV on the 26th bus in the IEEE-33 bus system. The voltage is further increased to 0.935246 p.u. at bus 18. Losses are further decreased to 0.305879 kVAR and 0.336049

kW, respectively. The FVSI, LSI, and LSF obtained are 0.020052, 0.010553, and 0.0012 respectively.

Table 4.6 Comparative analysis for VSI'S evaluated for Optimal placement (WCO technique) of PV on 26th bus in IEEE-33 bus system.

Optimal PV placement (WCO)							
Line no.	Bus no.	V (p.u)	Ploss (kW)	Qloss (kVar)	FVSI	LSF	LSI
-	1	1	-	-	-	-	-
1-2	2	0.997534	9.021452	4.719163	0.003911	0.0000723	0.00061
2-3	3	0.986126	35.83426	18.37198	0.014275	0.001580	0.000353
3-4	4	0.980632	12.33470	6.402445	0.021434	0.001601	0.001425
4-5	5	0.975306	11.32304	5.887499	0.008461	0.000449	0.000782
5-6	6	0.96137	22.62431	19.55027	0.0102	0.006104	0.000276
6-7	7	0.957902	2.149990	6.432442	0.020955	0.052528	0.042258
7-8	8	0.953124	4.997854	1.823012	0.074825	0.007781	0.017410
8-9	9	0.946931	4.356506	3.190963	0.013802	0.007101	0.000203
9-10	10	0.941189	3.752132	2.723342	0.014223	0.007275	0.000280
10-11	11	0.940341	0.823407	0.44354	0.006371	0.000378	0.000238
11-12	12	0.938862	1.142255	0.548993	0.014198	0.000218	0.001616
12-13	13	0.932826	2.880523	2.307969	0.03459	0.018380	0.000367
13-14	14	0.930588	0.994364	1.199947	0.029569	0.028263	0.004263
14-15	15	0.929194	0.632076	0.574826	0.003924	0.003861	0.000417
15-16	16	0.927844	0.558456	0.465508	0.010363	0.004187	0.000435
16-17	17	0.925844	0.529373	0.592508	0.017844	0.041862	0.000214
17-18	18	0.935246	0.336049	0.305879	0.020052	0.010553	0.001200
2-19	19	0.997006	0.445090	0.418737	0.003762	0.000596	0.000253
19-20	20	0.993433	1.115624	1.014387	0.0349	0.044109	0.000168
20-21	21	0.99273	0.384955	0.38289	0.009578	0.005547	0.000165
21-22	22	0.992094	0.327890	0.322934	0.017047	0.021241	0.000537
3-23	23	0.982551	3.444808	2.42484	0.014282	0.002422	0.000337
23-24	24	0.975899	5.393994	4.300137	0.110378	0.281749	0.000290
24-25	25	0.972585	1.563219	1.266025	0.111123	0.279203	0.03463
6-26	26	0.960525	1.636439	0.954025	0.003872	0.018481	0.000884
26-27	27	0.95803	3.513202	1.90929	0.00545	0.000269	0.000387
27-28	28	0.946813	11.24739	9.931247	0.013559	0.011295	0.000541

28-29	29	0.938764	7.884706	6.886594	0.036716	0.026341	0.000884
29-30	30	0.935318	4.064105	2.19058	0.245008	0.010557	0.007017
30-31	31	0.931176	1.832447	1.795334	0.044791	0.080063	0.001458
31-32	32	0.930263	0.491405	0.506689	0.020669	0.022307	0.002624
32-33	33	0.92998	0.297092	0.28519	0.009868	0.003963	0.000243

A comparative assessment of various voltage stability indices (VSI's) under 125% and 150% loading conditions is summarized in Tables 4.7 and 4.8, respectively. The evaluated indices remain within permissible thresholds, demonstrating sustained voltage stability even under stressed operating conditions.

Table 4.7 Comparative analysis of VSI's assessed at 125% of the system base case

125% load change of base case							
Line no.	Bus no.	V (p.u)	Ploss (kW)	Qloss (kVar)	FVSI	LSF	LSI
		1					
1-2	2	0.996242	19.92057	10.27511	0.003717	0.0000670	0.00066
2-3	3	0.978371	83.6225	42.712	0.013744	0.001534	0.000203
3-4	4	0.96886	32.50809	16.67654	0.020811	0.001574	0.001951
4-5	5	0.959451	30.59747	15.70426	0.008286	0.000448	0.000903
5-6	6	0.936005	62.31707	53.81495	0.010198	0.006393	0.000340
6-7	7	0.931601	3.402664	10.57323	0.020998	0.055305	0.003889
7-8	8	0.925403	8.183637	2.875834	0.075229	0.008236	0.005373
8-9	9	0.917402	7.131177	5.184416	0.013937	0.007586	0.000325
9-10	10	0.909978	6.120086	4.401777	0.014421	0.007836	0.000321
10-11	11	0.908875	1.192114	0.565442	0.006464	0.000391	0.000177
11-12	12	0.90695	1.730002	0.743339	0.01442	0.000233	0.00227
12-13	13	0.899151	4.663106	3.710478	0.035284	0.020036	0.000206
13-14	14	0.896276	1.482502	1.842475	0.030211	0.030912	0.002152
14-15	15	0.894481	0.871755	0.788145	0.004013	0.004234	0.000378
15-16	16	0.892737	0.747599	0.603633	0.010609	0.004595	0.000113
16-17	17	0.890173	0.698645	0.818511	0.018294	0.046149	0.000362
17-18	18	0.889399	0.371807	0.333919	0.020567	0.011630	0.000243
2-19	19	0.995581	0.536667	0.506126	0.003575	0.000561	0.004198

19-20	20	0.991105	1.589812	1.441667	0.033232	0.041946	0.000236
20-21	21	0.990224	0.442396	0.449996	0.009124	0.005272	0.000509
21-22	22	0.989428	0.352776	0.355839	0.016244	0.020221	0.000339
3-23	23	0.973855	5.332450	3.714646	0.013778	0.002357	0.018151
23-24	24	0.965453	8.449637	6.713007	0.106888	0.277213	0.027832
24-25	25	0.961264	2.329954	1.865978	0.107814	0.275749	0.030289
6-26	26	0.933557	4.528047	2.426893	0.003885	0.000144	0.000724
26-27	27	0.930305	5.721712	3.03375	0.005478	0.000282	0.000695
27-28	28	0.915716	18.76097	16.55582	0.013738	0.012154	0.000277
28-29	29	0.905242	13.09934	11.42946	0.037423	0.028676	0.001694
29-30	30	0.900741	6.660195	3.512923	0.250379	0.011427	0.008929
30-31	31	0.895373	2.901849	2.852225	0.045914	0.088232	0.001343
31-32	32	0.894191	0.634554	0.673535	0.021201	0.024600	0.004006
32-33	33	0.893824	0.305937	0.298943	0.010125	0.004358	0.000581

Table 4.8 Comparative analysis of VSI's assessed at 150% of the system base case

150% load change of base case							
Line no.	Bus no.	V (p.u)	Ploss (kW)	Qloss (kVar)	FVSI	LSF	LSI
1-2	2	0.995418	29.49277	15.15465	0.003589	0.000626	0.000468
2-3	3	0.973587	124.6961	63.63203	0.013379	0.001476	0.002272
3-4	4	0.961923	48.77697	24.96211	0.020351	0.001527	0.001364
4-5	5	0.950376	45.97184	23.53466	0.008141	0.000438	0.000106
5-6	6	0.921577	93.84029	81.0273	0.010141	0.006428	0.000141
6-7	7	0.916178	4.983381	15.79837	0.020928	0.055893	0.005534
7-8	8	0.908558	12.22015	4.209801	0.075231	0.008372	0.007255
8-9	9	0.898711	10.66461	7.723000	0.013999	0.007783	0.000593
9-10	10	0.889572	9.139716	6.542127	0.014546	0.008108	0.000586
10-11	11	0.888211	1.662776	0.721052	0.006524	0.000039	0.000276
11-12	12	0.885838	2.481062	0.991687	0.014571	0.000239	0.000125
12-13	13	0.876229	6.944300	5.505286	0.035815	0.020989	0.000179
13-14	14	0.872693	2.107682	2.665390	0.030717	0.032495	0.012281
14-15	15	0.870483	1.179220	1.061794	0.004085	0.004462	0.000321
15-16	16	0.868333	0.990407	0.780948	0.010810	0.004851	0.000293

16-17	17	0.865179	0.91611	1.108857	0.018668	0.048896	0.000257
17-18	18	0.864225	0.417758	0.369951	0.020998	0.012325	0.000228
2-19	19	0.994623	0.649009	0.61333	0.003453	0.000531	0.005174
19-20	20	0.989242	2.171992	1.966256	0.032155	0.039955	0.000342
20-21	21	0.988183	0.512937	0.532407	0.008831	0.005021	0.000142
21-22	22	0.987225	0.383347	0.396258	0.015728	0.019284	0.000388
3-23	23	0.968123	7.671455	5.312862	0.013439	0.002276	0.000644
23-24	24	0.957957	12.23861	9.704945	0.104654	0.27045	0.072040
24-25	25	0.952887	3.282068	2.610986	0.105762	0.270054	0.018987
6-26	26	0.918571	6.704689	3.535587	0.003868	0.000144	0.000398
26-27	27	0.914576	8.517591	4.457268	0.005464	0.000284	0.000448
27-28	28	0.896629	28.28472	24.95274	0.013813	0.012496	0.000370
28-29	29	0.883745	19.71375	17.19178	0.037850	0.029833	0.000990
29-30	30	0.878218	9.955424	5.19138	0.253891	0.011871	0.008979
30-31	31	0.871587	4.26410	4.198538	0.046707	0.092904	0.001123
31-32	32	0.870126	0.816979	0.886159	0.021583	0.025929	0.024218
32-33	33	0.869672	0.317213	0.316474	0.010310	0.004586	0.000280

Table 4.9, which compares the overall losses, makes it evident that the suggested WCO approach, when used to place solar PV generation optimally, results in lower losses (192.4910 kW) compared to the base case (252.6703 kW) and PSO algorithm placement (252.6703 kW).

Table 4.9 Comparative analysis of total losses for various cases

	Ploss (kW)	Qloss(kVar)	Total Loss kW
Base case (Without DG)	210.9901	143.6413	252.6703
PSO (with PV at 28 bus)	184.8685	128.0079	224.7932
WCO (with PV at 26 bus)	157.9331	110.1292	192.4910
125% load change in the base case	337.2071	227.4549	406.3225
150% load change in the base case	501.969	337.656	603.8035

Table 4.10 summarizes the comparison of power loss reduction achieved through WCO and other optimization methods suggested in literature for IEEE 33 bus system. Numerous DG placement techniques from the literature are compared, and it is discovered that the suggested method performs better than those suggested in [193-195].

Table 4.10 Power loss comparison of WCO with literature methods in IEEE 33-bus system

Techniques	DG Location	Min Voltage (p.u.)	Ploss (kW)
Genetic algorithm [193]	29	0.921	165.98
Simulated annealing [194]	13	0.918	178.28
Artificial bee colony [195]	30	0.913	181.89
PSO (used for comparison)	28	0.917	184.86
WCO (Proposed method)	26	0.925	157.93

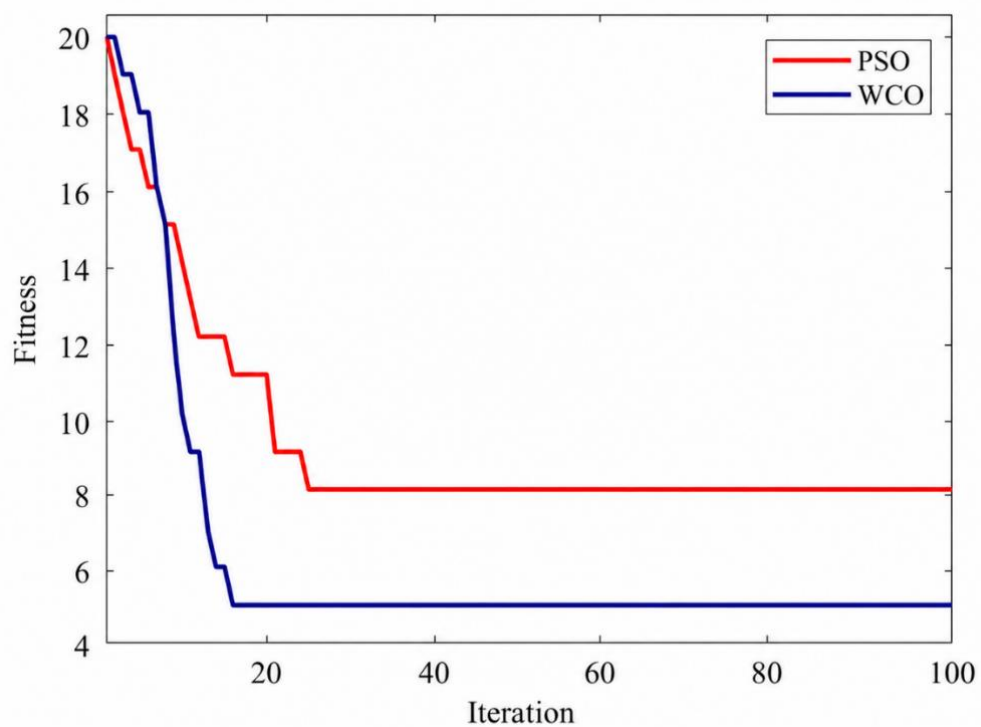


Figure 4. 15 Convergence Comparison WCO Vs PSO

A comparison of the fitness convergence of the PSO algorithm and the suggested WCO methodology is shown in Figure 4.15. The suggested method clearly converges more quickly and stabilizes at an ideal value with a notably lower number of iterations. This confirms the effectiveness of the proposed strategy over traditional optimization methods by highlighting its improved convergence rate, as well as by reflecting reduced computational effort and enhanced robustness.

4.6.4 Results and Discussion with Optimal Placement of EVCS, PV and Wind

The results show that EVCS alone increases voltage stress and losses. Optimal EVCS placement improves stability, but the coordinated integration of PV and wind provides the best performance, significantly enhancing voltage profile, stability indices, and loss reduction. The results are taken for following cases:

Case 1: Distribution IEEE 33 Base case

Case 2: Distribution IEEE 33 with EVCS and without DG

Case 3: Distribution system with EVCS and solar PV

Case 4: Distribution system with EVCS and wind turbine

Case 5: Distribution system with solar PV, wind and EVCS.

Case 6: Distribution IEEE 33 with random EVCS placement

Figure 4.16 shows voltage profile of 33-bus system for various case listed above. It can be seen that with coordinated EVCS-PV and Wind the voltage profile further improves. The active and reactive power losses are further reduced as shown in Figure 4.17 and 4.18 respectively.

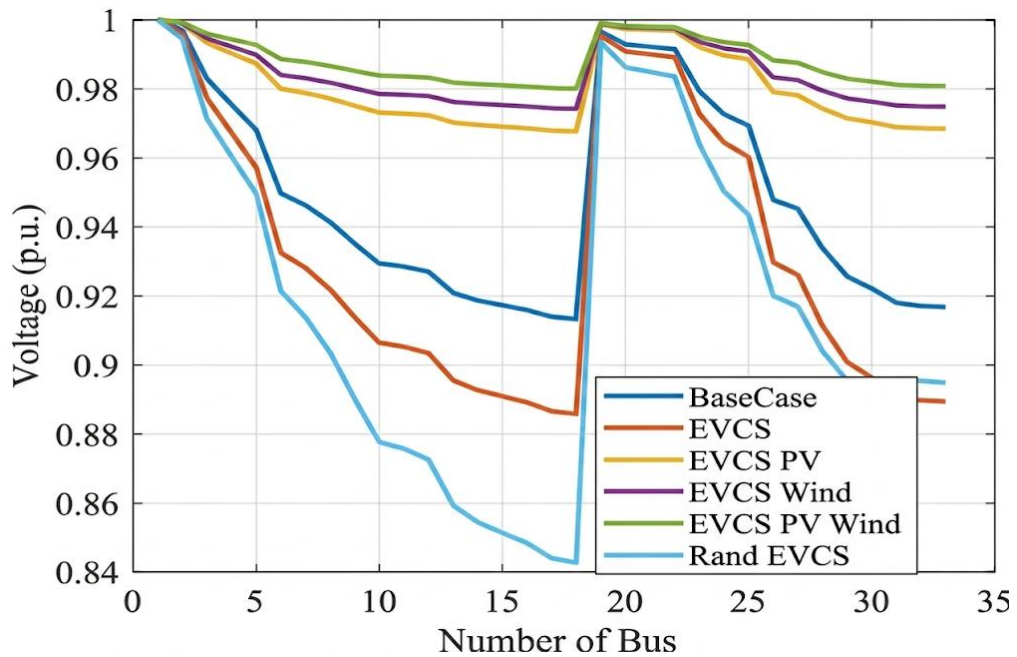


Figure 4.16 Voltage profile for various cases

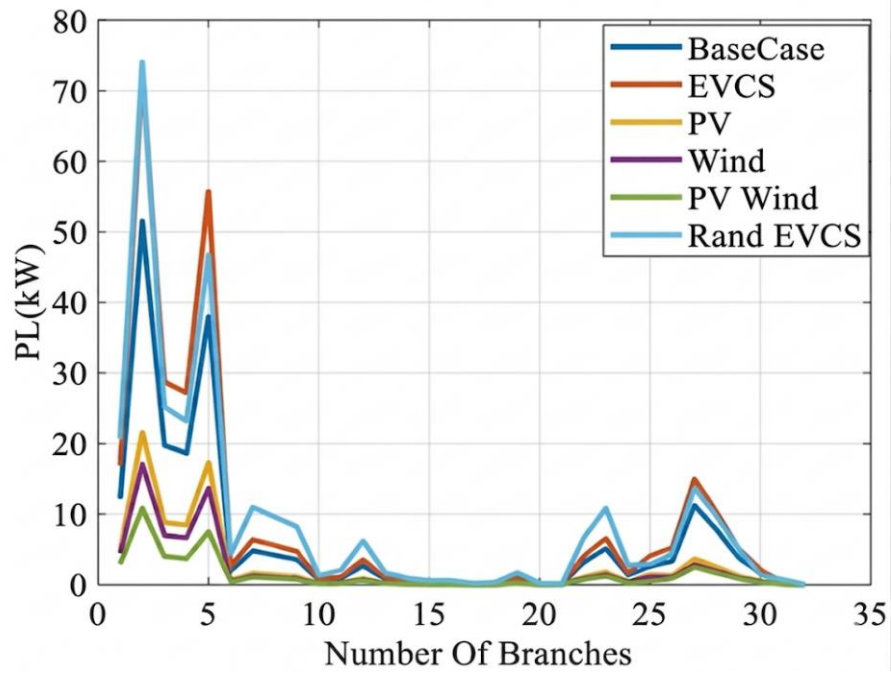


Figure 4.17 Active power loss

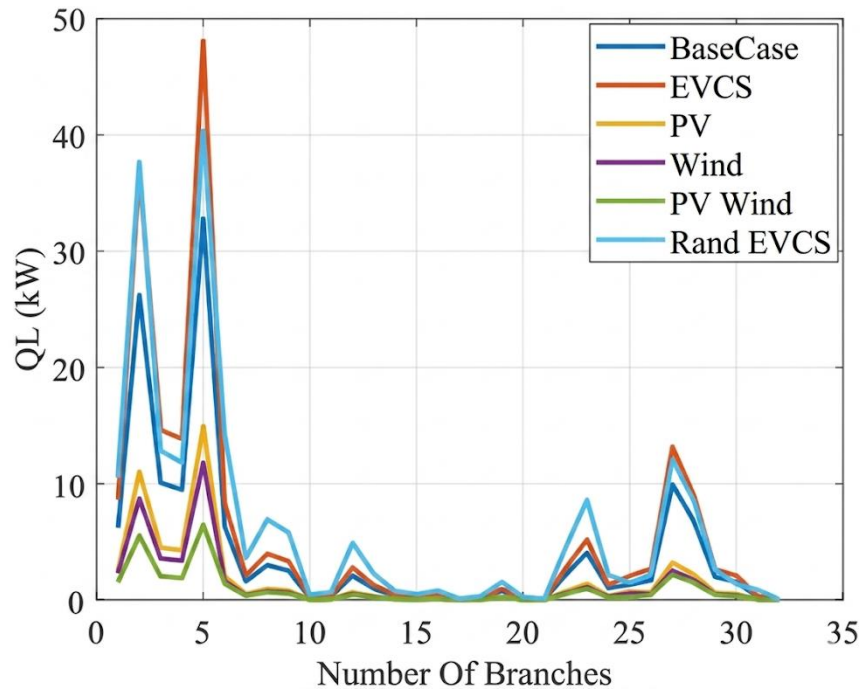
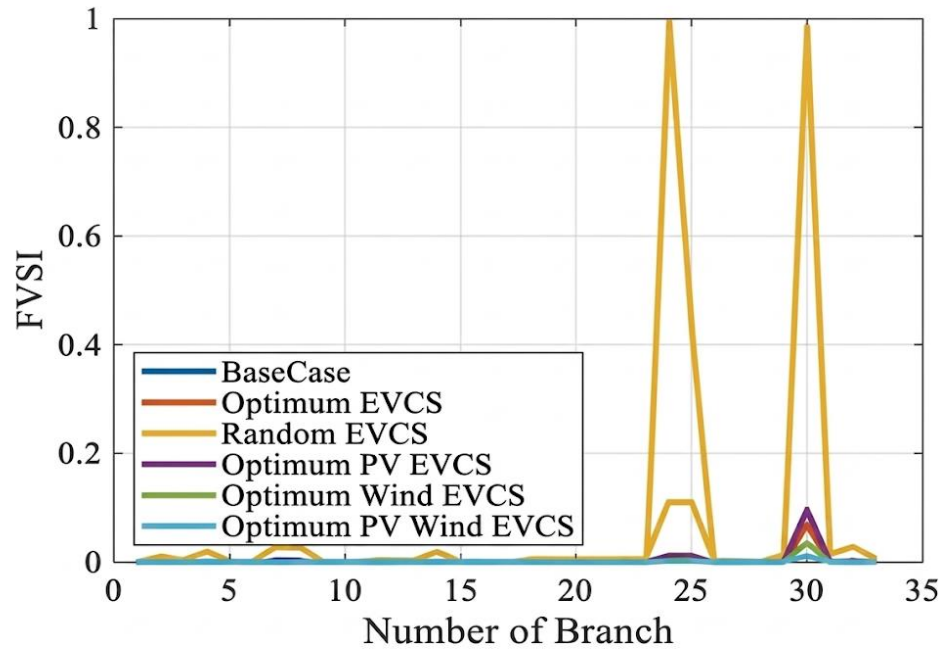
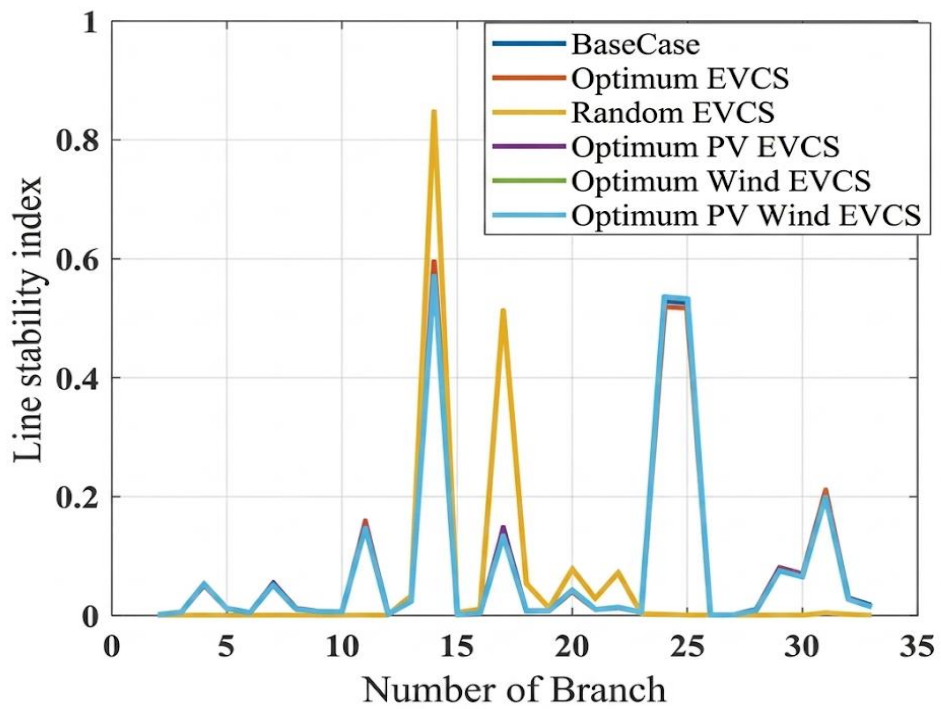


Figure 4.18 Reactive power loss

Figure 4.19 a, b and c illustrates the variation of the FVSI, LSI and LSF respectively across all buses of the IEEE 33-bus radial distribution system under four operating scenarios. After placing EVCS-PV-wind optimally the index values significantly enhance below unity for all the branches showing stable system operation.



(a)



(b)

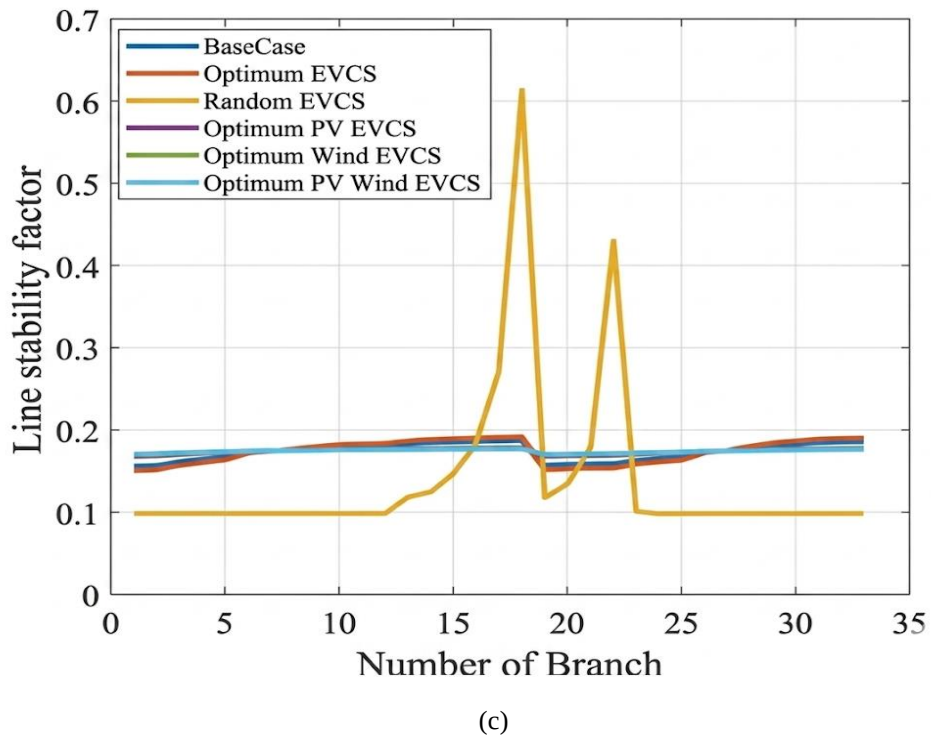


Figure 4.19 VSI's for 33 IEEE system (a) Line Stability Factor (b) Fast Voltage Stability Index (c) Line Stability Index

The comparison of total active loss is shown in Figure 4.20 which clearly shows that optimally placing EVCS with solar PV and wind generation gives reduced losses against base case and random placement and all other scenarios. It reduced to 53.6286 kW.

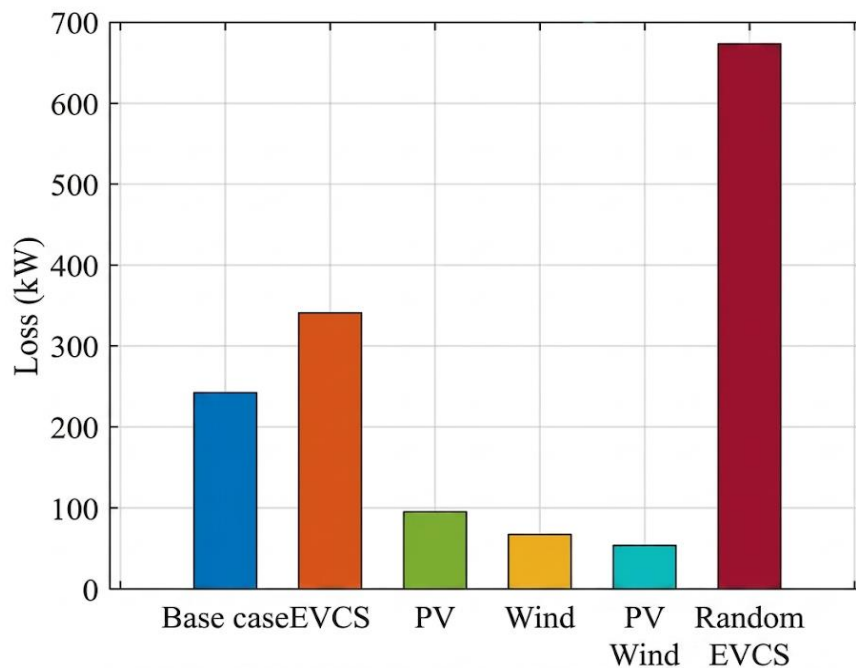


Figure 4.20 Comparison of total losses

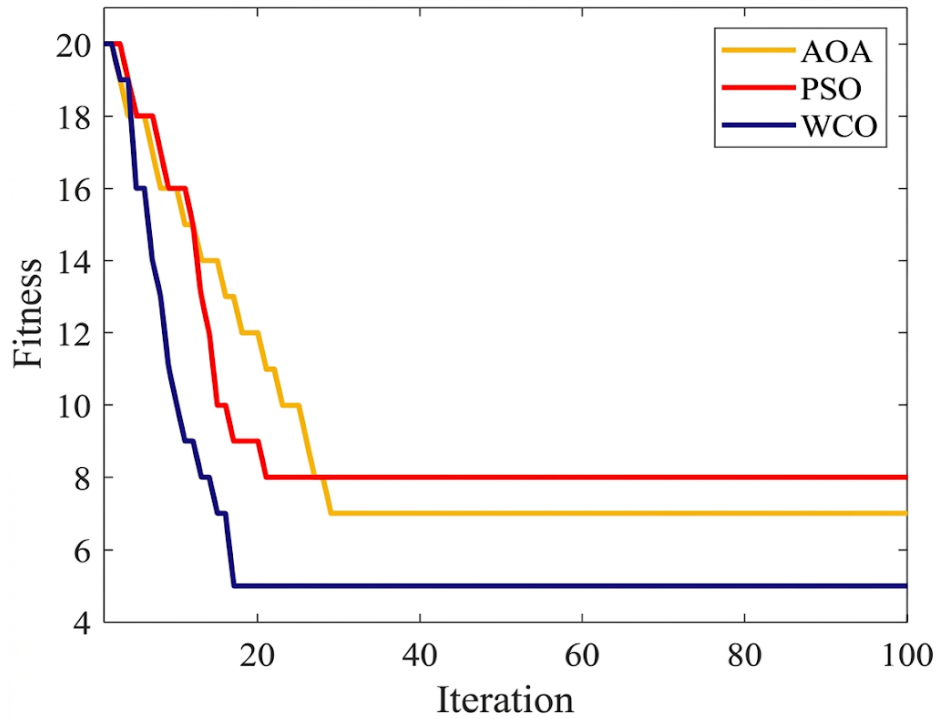


Figure 4.21 Comparison of proposed algorithm

Figure 4.21 presents a comparative performance analysis of the proposed algorithm against the existing Arithmetic Optimization Algorithm (AOA) [146] and Particle Swarm Optimization (PSO) [147]. The results demonstrate that the proposed approach converges to a stable optimal solution with significantly fewer iterations. This faster convergence and improved stability highlight the superior efficiency and effectiveness of the proposed algorithm compared to the benchmark methods.

4.7 Summary

This chapter presented the application of the World Cup Optimization (WCO) algorithm for the optimal placement of solar PV and wind generation units in the IEEE-33 bus distribution system, with the objective of improving voltage profile, minimizing active power losses, and enhancing voltage stability indices (FVSI, LSI, and LSF). Considering the adverse impact of EVCS integration on system performance, coordinated deployment of renewable sources was essential to support weak buses and maintain network stability.

A comprehensive analysis was carried out under six scenarios, namely: base case, random EVCS placement, optimal EVCS placement, PV-EVCS, Wind-EVCS, and combined PV-Wind-EVCS integration. The results demonstrated significant performance improvement

with optimal renewable integration. The minimum bus voltage increased from 0.88575 p.u. (optimal EVCS case) to 0.96814 p.u. with PV placement, further to 0.97460 p.u. with wind integration, and reached 0.97974 p.u. under coordinated PV-Wind-EVCS operation. Voltage stability indices showed remarkable enhancement, where FVSI reduced from 0.00439 to 0.000305, LSI improved from 0.053916 to 0.008365, and LSF decreased from 0.6134695 to 0.176835. Additionally, active power losses were significantly reduced from 670.0882 kW to 341.0856 kW with optimal EVCS placement and further minimized to 53.6286 kW in the combined PV-Wind-EVCS scenario.

The comparative results confirmed that the WCO algorithm outperforms conventional PSO in terms of convergence speed, solution quality, and global search capability. Furthermore, validation on the IEEE-69 bus system established the robustness, scalability, and effectiveness of the proposed methodology across different network configurations.

Despite these improvements in steady-state performance and voltage stability, the integration of renewable energy sources introduces challenges related to dynamic behavior, grid synchronization, and power quality under varying operating conditions. Therefore, the subsequent chapter focuses on the design and implementation of an advanced Complex Band Pass Filter–Frequency Locked Loop (CBF-FLL) based controller. The proposed controller aims to achieve real-time voltage regulation, enhanced power quality, and fast and robust grid synchronization, thereby ensuring stable and reliable operation of inverter-based renewable energy systems under grid variability.

CHAPTER - 5

CBF-FLL BASED GRID INTEGRATION OF SOLAR PV FOR VOLTAGE & POWER QUALITY IMPROVEMENT

This chapter focuses on the design and implementation of an advanced Complex Band-Pass Filter -Frequency Locked Loop (CBF-FLL) based control strategy for the grid integration of solar photovoltaic (PV) systems. With the increasing penetration of inverter-based renewable energy sources, maintaining voltage stability, synchronization, and power quality at the point of common coupling (PCC) has become a significant challenge, particularly under weak grid and nonlinear loading conditions.

To address these challenges, a robust CBF-FLL control approach is developed to achieve accurate and fast grid synchronization, effective voltage regulation, and mitigation of power quality issues such as harmonics and voltage distortions. The proposed controller enhances the dynamic performance of the grid-connected PV system under varying irradiance, load disturbances, and grid uncertainties.

The effectiveness of the CBF-FLL strategy is evaluated through detailed simulations, demonstrating its capability to maintain stable operation, improve voltage profile, and ensure compliance with power quality standards, thereby enabling reliable integration of solar PV into modern power systems.

5.1 Introduction

Renewable technologies are developing quickly as a result of the growing demand for sustainable and clean energy on a worldwide scale. Due to their dependability, environmental friendliness, scalability, and falling installation costs, solar photovoltaic (SPV) systems have become the most widely used. Grid-connected SPV systems are especially favored because they facilitate power exchange between the generating system and the utility grid, providing dependable and economical operation.

However, there are a number of technical difficulties when integrating SPV systems into the electrical grid, particularly when there are non-linear loads at the PCC. Harmonics are introduced into the system when non-linear loads pull non-sinusoidal currents. These harmonics lead to problems with power quality, including increased grid current THD, component overheating, and possible damaging to delicate electronic equipment. IEEE-519 standards [198] state that eliminating harmonic distortion and preserving sinusoidal grid currents are essential for safe and effective grid operation.

Accurate synchronization between the grid voltage and inverter current is essential to ensure effective power exchange in a grid-connected solar photovoltaic (SPV) system. The overall performance of the system largely depends on the control strategy adopted for inverter operation. To inject a clean sinusoidal current into the utility grid, various advanced control approaches have been developed. These techniques typically generate reference current signals according to real-time system conditions such as grid voltage, frequency, and load dynamics. The generated references are then processed by the controller to produce appropriate gating pulses for the power electronic switches of the inverter, thereby ensuring stable operation, improved power quality, and reliable grid interaction.

Due to their simple implementation and sufficient steady-state precision, Phase-Locked Loop (PLL)-based techniques have long been widely employed for grid synchronization. When PLL structures are exposed to low Short Circuit Ratio (SCR), frequency drift, voltage imbalance, or distorted grid voltages, they exhibit a number of performance problems, including phase inaccuracy, slow dynamic response, and increased harmonic injection. These limitations become more apparent in weak-grid situations where renewable energy sources are widely used.

Frequency Locked Loop (FLL)-based techniques, particularly Second-Order Generalized Integrator FLL (SOGI-FLL), have attracted attention as a solution to these issues due to their improved frequency tracking and harmonic rejection. Phase-Locked Loop (PLL)-based techniques have historically been widely used for grid synchronization due to their simplicity. SOGI-FLL structures are more resilient and have built-in filtering of essential components as compared to classical PLLs. Other innovations such as Dual-SOGI (DSOGI-FLL) improve the accuracy of synchronization in distorted grids by allowing positive- and negative-sequence separation in imbalanced situations [199-206]. Even though SOGI-based structures have made progress, they may still perform poorly under extreme nonlinear loads

and high harmonic content, and adjusting the parameters is essential to their dynamic response.

In recent years, advanced synchronization algorithms have been supplemented with adaptive estimating and selective filtering approaches to enhance dynamic stability and disturbance rejection. In particular, by adding a Complex Band-Pass Filter to the FLL structure, harmonic distortion is attenuated, enabling direct extraction of the fundamental frequency component. Unlike conventional PLL-based methods that primarily rely on phase error minimization, the CBF-FLL methodology improves noise immunity, weak-grid tolerance, and transient response by integrating harmonic-selective filtering directly into the synchronization loop.

By improving synchronization and converter techniques, several researchers have tried to improve grid interaction. While [207] suggested a robust architecture for PV-wind-battery systems with unbalanced voltages, [208] created active power coefficient control to reduce distortion effects. [209] enhanced harmonic performance using PLL-based methods that were optimized. PLL-derived structures are still sensitive to noise, frequency variations, and harmonics, though. Although they improve voltage control, hardware-oriented improvements like the high-gain converter in [210] do not really fix synchronization issues. However, research on the application of a stand-alone CBF-FLL approach created specifically for grid-connected solar PV systems is currently lacking.

This work proposes a novel implementation of the CBF-FLL technique for enhancing synchronization, power quality, and voltage stability in grid-tied solar PV systems, particularly under the influence of non-linear loads. In the proposed control strategy, the algorithm begins by sensing the non-linear load currents at the PCC. The embedded Complex Band-Pass Filter within the FLL filters out harmonic components and isolates the fundamental frequency component from the distorted load current [211]. This enables the inverter to inject clean, sinusoidal current into the grid, even under distorted load conditions.

Developing and modelling a control algorithm for a double-stage, three-phase grid-connected SPV system using the CBF-FLL technique is the primary goal of this work. The suggested control technique is intended to maintain low THD levels in grid currents and guarantee stable operation under a variety of abnormal conditions, such as zero irradiance, abrupt changes in non-linear demand, variable solar irradiance, unbalanced loading and weak grid condition.

5.2. Problem Statement-3

- Conventional power systems maintain stability through the inherent inertia and slow dynamics of large synchronous generators, which effectively dampen transient disturbances and preserve system equilibrium during faults and load variations.
- In contrast, inverter-interfaced DERs and grid-following converters have fast dynamics but lack stabilizing inertia, creating a tradeoff between rapid response and transient stability. As a result, microgrids often face transient performance issues where high-speed control can compromise voltage regulation and power quality.
- However, the regulation of the microgrid's voltage is very much influenced by the type of control strategy that is employed.
- The control algorithms are used for enhancing the performance of the microgrids under dynamic/ transient conditions.
- The objective of control technique is used to mitigate the grid currents harmonics, inject the surplus active power into the grid with unity power factor together with compensating the reactive power demand of the load in the grid connected mode.
- Control Challenges for Integration of PV System to Grid are Extraction of maximum PV power during dynamic changes in irradiance, Power exchange with the grid at unity power factor (UPF), Harmonics mitigation of loads connected at Point of Common Coupling (PCC), Balancing the grid currents and hence voltage during unbalanced load conditions and Effective utilization of VSC during unavailability of PV power.
- Advanced control for grid-following converters ensuring robust transient stability, voltage regulation, and power quality in inverter-dominated microgrids with RES/EV integration.

5.3 Proposed Methodology for Problem Statement-3

With rising inverter dominance in modern grids, the proposed research develops an advanced Complex Band Pass Filter based Frequency Locked Loop (CBF-FLL) synchronization and reference generation technique for Grid-Following (GFL) inverters, delivering:

- Continuous Voltage Support: Real-time voltage regulation ($\pm 5\%$ limits) under intermittent renewable generation and EV charging loads
- Power Quality Enhancement: Harmonic mitigation and unity power factor operation.
- Robust Performance: Seamless operation during unbalanced conditions and weak grids (low SCR).

Key Innovations:

- Superior frequency/phase tracking compared to conventional PLLs/FLLs
- Enhanced transient stability addressing inertia-less inverter challenges
- Grid-supportive features for Indian distribution networks with high RES/EV penetration.

5.4 Grid Tied Solar PV system Configuration

The grid connected dual-stage solar PV system architecture is shown in Figure 5.1. The suggested grid-connected solar PV system is intended to provide reliable and effective energy injection into the utility grid. A DC–DC converter is used in the first stage to process the DC output produced by the solar PV array. This converter uses maximum power point tracking (MPPT) and voltage regulation to maximize energy extraction under changing temperature and irradiance circumstances.

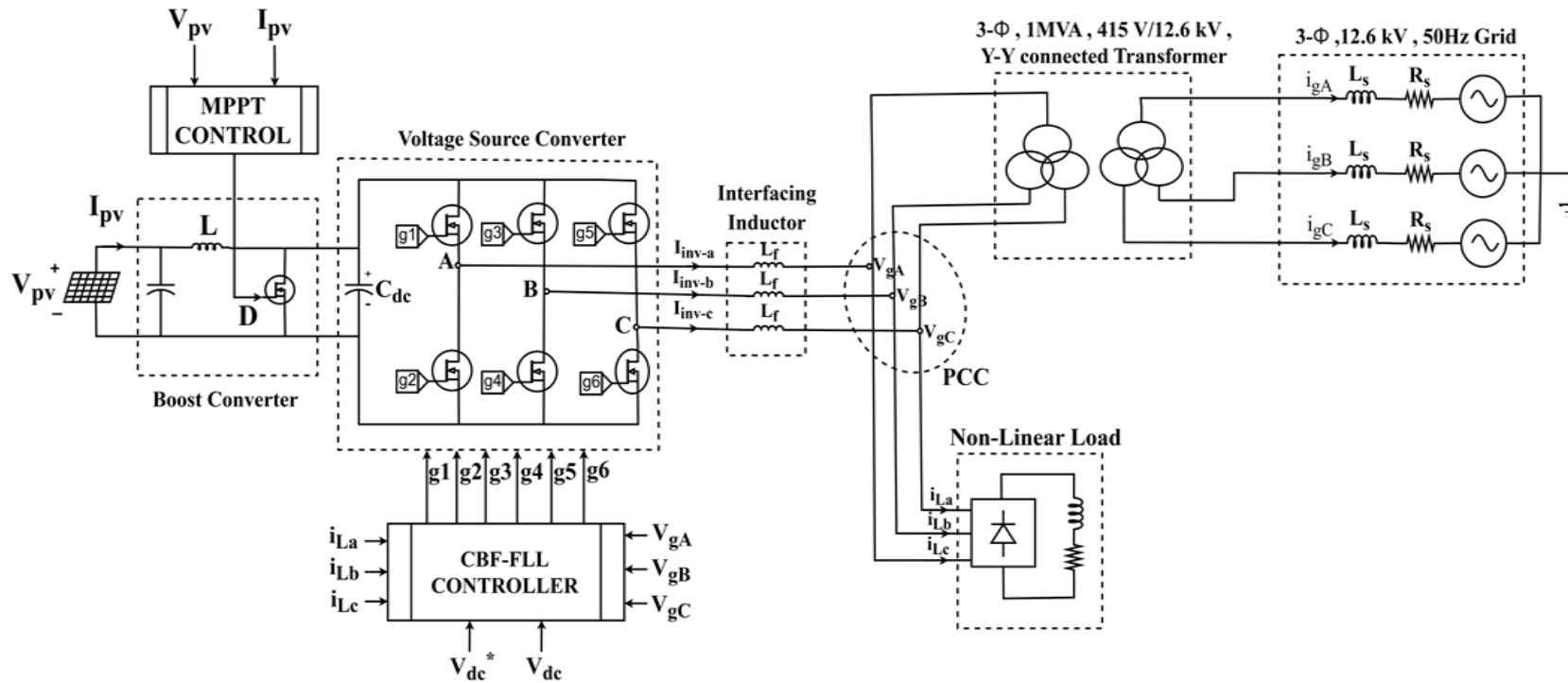


Figure 5.1 Proposed dual stage solar PV system connected to grid

In the second stage, a grid-tied inverter receives the regulated DC power and transforms it into synchronized AC power. At the PCC, a step-up transformer interfaces the inverter output with the utility grid and supports local loads. Voltage support, harmonic reduction, and steady operation under dynamic grid conditions are made possible by the overall system structure, as shown in Figure 5.1, which permits controlled power exchange with the grid.

5.5 Design of Solar PV System

5.5.1 PV Array Configuration

The grid-connected PV system is designed to deliver a total power capacity of 775 kW, regulated through a 400 V DC bus. Based on the electrical specifications of the selected PV module, the PV array configuration is systematically derived to meet the required capacity. The corresponding I-V and P-V characteristics of the module, which illustrate its electrical behavior under standard test conditions, are presented in Figure 5.2. If voltage and current of solar panel at maximum power point are $V_{mp} = 54.7V$ and $I_{mp} = 5.58A$, then,

No. of panels to be connected in series will be:

$$N_s = \frac{V_{mp}(array)}{V_{mp}} = \frac{400}{54.7} = 8 \quad (5.1)$$

Also, $P_{mp} = V_{mp} * I_{mp} = 54.7 * 5.58 = 305.226 \text{ W}$

No. of panels to be connected in parallel will be:

$$N_p = \frac{P_{mp}(array)}{P_{mp} * N_s} = \frac{775k}{305.226 \times 8} = 318 \quad (5.2)$$

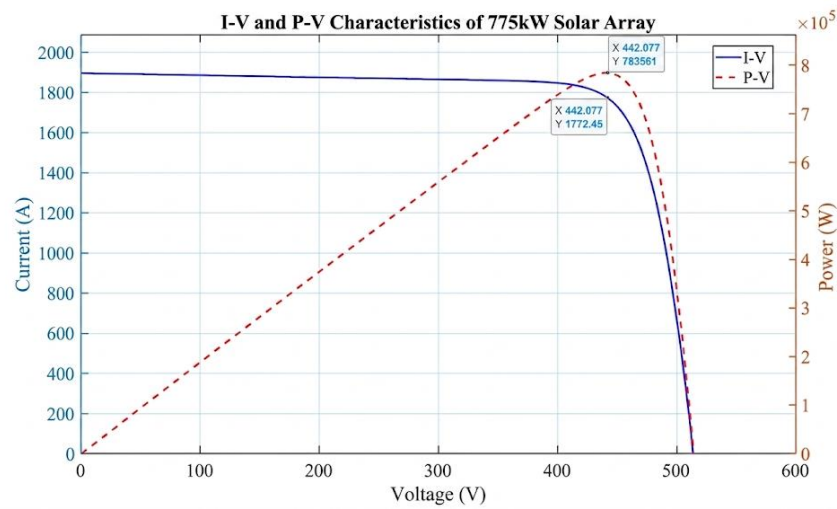


Figure 5.2 I-V and P-V characteristics of Solar PV array

Table 5.1 presents the specifications and electrical parameters of the 775kW solar photovoltaic (PV) array used in the proposed system for simulation and performance analysis.

Table 5.1 Parameters of 775 kW solar array

Parameter	Value
Voltage at MPP module (V_{mp})	54.7 V
Current at MPP module (I_{mp})	5.58 A
Maximum Power (P_{mp})	305.226 W
Open circuit voltage (V_{oc})	32.9 V
Short circuit current (I_{sc})	8.21 A
Number of parallel string (N_p)	318
Number of series module per string (N_s)	8
Voltage at MPP array ($V_{mp(array)}$)	437.6 V
Current at MPP array ($I_{mp(array)}$)	1774.44 A
Rated array power ($P_{mp(array)}$)	775 kW

5.5.2 Boost Converter Design

To increase the array voltage from 400V to a regulated 700V DC bus, a DC-DC boost converter is fitted between the PV array and the inverter. This voltage increase improves power transfer efficiency, guarantees appropriate DC-link conditioning, and gives the grid-tied inverter stage a stable operating point [213]. Key design parameters known for boost converter are $V_{in} = 400V$; $V_{out} = 700V$; $f = 20 \text{ kHz}$; $P = 775 \text{ kW}$;

The required duty cycle of the boost converter is calculated as:

$$D = 1 - \frac{V_{in}}{V_{out}} = 1 - \frac{400}{700} = \frac{3}{7} \quad (5.3)$$

Input current of boost converter is found as:

$$I_{in} = \frac{P}{V_{in}} = \frac{775 \text{ kW}}{400V} = 1937.5A \quad (5.4)$$

The boost inductor value is determined by considering the inductor current ripple to be 30% of the input current, ensuring optimal converter performance and maintaining acceptable current ripple limits in the PV system.

$$\Delta \dot{I}_L = 0.3 \times 1937.5 = 581.25A$$

Thus, the value of inductor (L) is calculated as:

$$L = \frac{D \times V_{in}}{f \times \Delta I_L m} = \frac{\frac{3}{7} \times 400}{20k \times 518.25} = 29.4 \mu H \quad (5.5)$$

By ensuring continuous conduction mode (CCM) operation with controlled current ripple, this chosen inductor value supports consistent MPPT performance and preserves high power-conversion efficiency.

5.5.3 Selection of Interfacing Inductor

According to [206], the value of the per phase interface inductor is determined by assuming that the ripple current is approximately 3% of the maximum solar current.

$$L_f = \frac{\sqrt{3} * m * V_{dc}}{12 * h * f * \Delta i} \quad (5.6)$$

Where, m -modulation index =1; V_{dc} - DC link voltage = 700 V; h - overloading factor = 1.2; f - switching frequency = 10 kHz; Δi - ripple in inductor current = 3% of $I_{mp} = 0.03 * 1774.44 = 53.23$ A. Thus, L_f is calculated as per eq (5.6) and its value obtained is nearly 157.98 μH .

5.5.4 Selection of DC-Link capacitor

The DC-link capacitance is determined following the method described in [214], where the allowable ripple voltage is limited to approximately 2% of the boost converter output voltage.

$$C_{dc} = \frac{I_{mp(array)}}{2 * 2\pi f * \Delta v_c} \quad (5.7)$$

Where, $I_{mp(array)}$ - current at MPP = 1774.44 A; f - fundamental frequency on AC side of inverter = 50 Hz; Δv_c - ripple in voltage = 2% of $V_{dc} = 0.02 * 700 = 14$ V. Thus, C_{dc} is calculated as per eq (5.7) and its value obtained is nearly 0.2017 F.

5.5.5 Grid Specifications

The PV system connects to a balanced three-phase distribution grid that runs at a nominal frequency of 50 Hz and a line-to-line voltage of 415 V. The grid serves as the main power exchange interface and a reliable voltage reference for evaluating the suggested control strategy's dynamic and steady-state performance.

5.5.6 Load Configuration at PCC

A nonlinear load of 100 kW, modeled as a three-phase uncontrolled diode rectifier feeding an R-L load ($R=3.143 \Omega$, $L=50\text{mH}$), is connected at the PCC to introduce harmonic distortion and evaluate the inverter's power quality performance under distorted loading conditions.

5.6 Control Technique

The proposed system employs a double-stage converter topology to interface the solar photovoltaic system with a three-phase grid via a DC-link. The control strategy depicted in Figure 5.1 is primarily aimed at two objectives: extracting the maximum available power from the SPV system and delivering it efficiently into the grid while improving power quality at the PCC. The control scheme consists of two major functions: Maximum Power Point Tracking control and Voltage Source Converter (VSC) control.

5.6.1 MPPT Algorithm

The MPPT operation is carried out using a DC-DC boost converter, with its duty cycle regulated by the Incremental Conductance (InC) algorithm. The InC method is chosen over conventional techniques due to its higher precision and better tracking performance under rapidly changing environmental conditions [222-225].

The InC MPPT algorithm is based on the idea that at the maximum power point ($\frac{dp}{dv} = 0$), the derivative of PV power with respect to voltage is zero. The algorithm identifies whether the operating point is to the left or right of the MPP by comparing the incremental conductance ($\frac{dI}{dV}$) with the instantaneous conductance ($\frac{I}{V}$) and then modifies the reference voltage to track it efficiently [226-228]. Figure 5.3 illustrates the MPPT characteristics corresponding to this behavior.

- On left of MPPT, $\frac{dp}{dv} > 0 \rightarrow \frac{dI}{dV} > -\frac{I}{V} \rightarrow \text{Increase Voltage}$
- On right of MPPT, $\frac{dp}{dv} < 0 \rightarrow \frac{dI}{dV} < -\frac{I}{V} \rightarrow \text{Decrease Voltage}$
- On left of MPPT, $\frac{dp}{dv} = 0 \rightarrow \frac{dI}{dV} = -\frac{I}{V} \rightarrow \text{MPP Reached}$

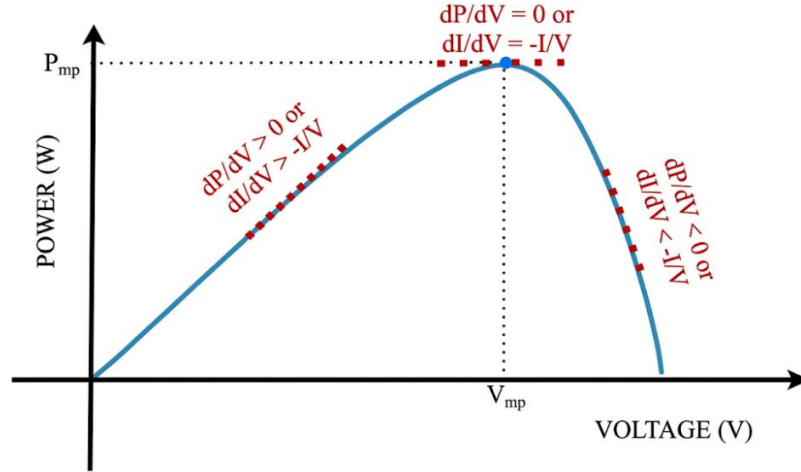


Figure 5.3 InC MPPT Characteristics

5.6.2 VSC Control

To control the Voltage Source Converter (VSC), the control system is divided into three main parts: Unit template generation, the CBF-FLL, and DC-link voltage regulation using a PI controller. The schematic diagram is shown in Figure 5.4.

While Complex Band-Pass Filter Frequency Locked Loop structures have been applied previously for robust grid synchronization, their direct use for reference-current estimation in grid-connected inverter control has not been established. This work therefore proposes a unified CBF-FLL based reference generation scheme that simultaneously extracts the positive-sequence fundamental phasor and provides clean, low-latency current references for the VSC control loops. The proposed approach offers enhanced harmonic and unbalance rejection, improved stability in low-short circuit ratio (SCR) conditions, and reduced implementation complexity compared with multi-stage filtering and conventional PLL/SOGI-based reference generation methods.

This is the first study demonstrating the CBF-FLL's efficacy for reference current estimation and its coordinated interaction with MPPT and DC-link control in a dual-stage PV system. This filter configuration offers a selective passband centered at the fundamental frequency ω_g , significantly improving frequency estimation in distorted environments.

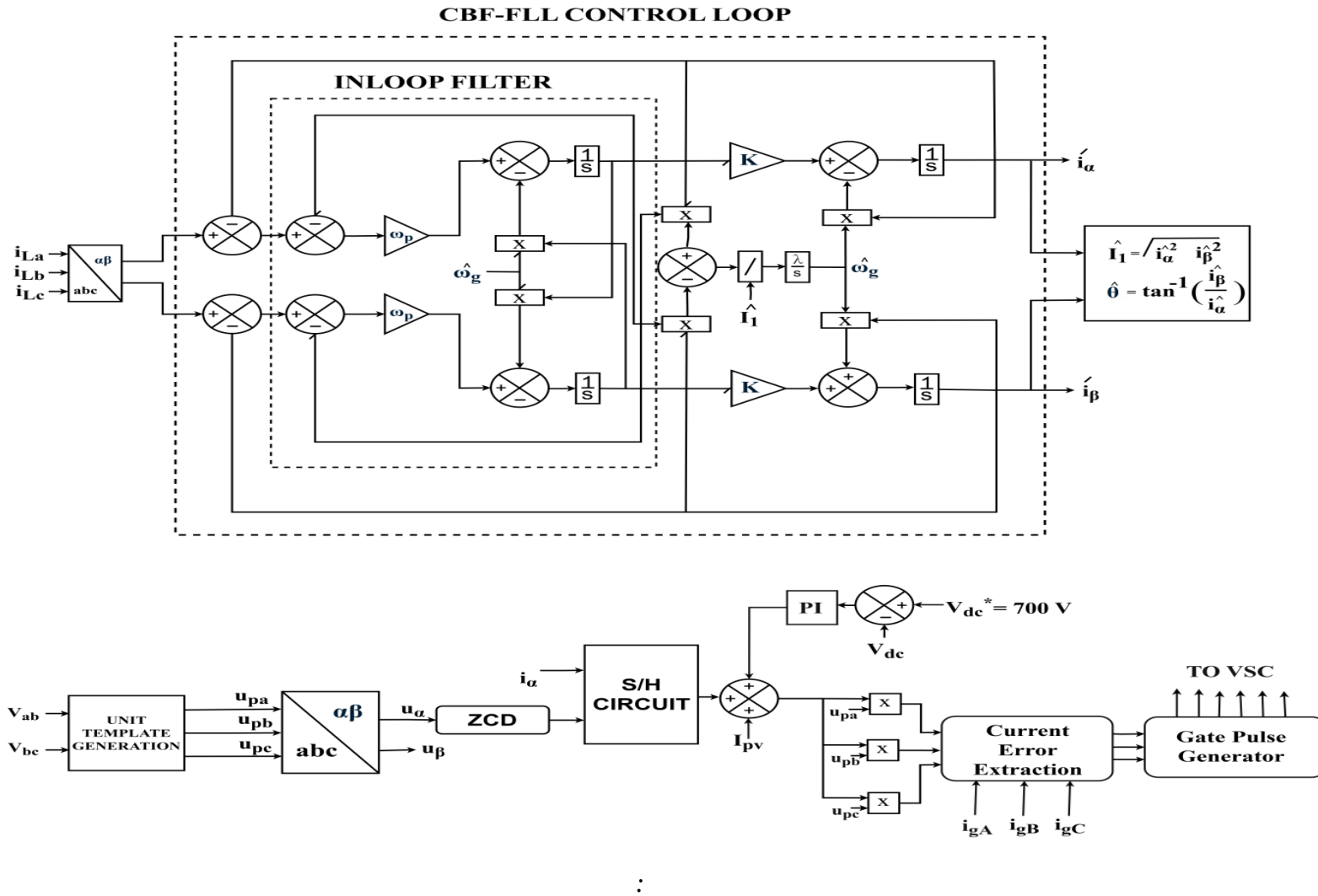


Figure 5.4 Control Structure based on CBF- FLL

5.6.3 Unit Template Generation:

Unit templates serve as reference signals for the current control loop. These templates ensure that the injected current is sinusoidal and phase-aligned with the grid voltage, thereby enhancing power transfer and maintaining voltage quality at the PCC. For a three-phase grid, three-unit templates one for each phase are generated which have unit peak amplitude. These are referred to as *in-phase unit templates*. The fundamental current component output, I_{fa} for phase ‘a’ is used to indicate when, with the phase voltage of PCC, the load current is in phase. In mathematical terms, it is expressed as,

$$I_{fa} = I_{peak} \sin(\omega t - \phi) \quad (5.8)$$

Expanding using trigonometric rules and solving, we get,

$$I_{fa} = (I_{peak} \cos \phi) \text{ for } \cos \omega t = 0 \quad (5.9)$$

In all three phases, in-phase components are obtained similarly.

To compute the unit templates, only two of the three-line voltages from the grid are sensed. Using these, the three-phase voltages are reconstructed based on the assumption of a balanced system.

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & \frac{1}{3} \\ -\frac{1}{3} & \frac{1}{3} \\ -\frac{1}{3} & -\frac{2}{3} \end{bmatrix} \cdot \begin{bmatrix} Vab \\ Vbc \end{bmatrix} \quad (5.10)$$

The peak amplitude of the phase voltage is then extracted,

$$V_t = \sqrt{\frac{2(Va^2 + Vb^2 + Vc^2)}{3}} \quad (5.11)$$

Subsequently, each phase voltage is normalized by dividing it with the extracted peak value to generate the in-phase unit templates.

$$u_{pa} = \frac{Va}{V_t}, \quad u_{pb} = \frac{Vb}{V_t}, \quad u_{pc} = \frac{Vc}{V_t} \quad (5.12)$$

The quadrature unit templates are

$$u_{qa} = -\frac{u_{pb}}{\sqrt{3}} + \frac{u_{pc}}{\sqrt{3}}, \quad u_{qb} = \frac{\sqrt{3}u_{pa}}{2} + \frac{(u_{pb} - u_{pc})}{2\sqrt{3}}, \quad u_{qc} = -\frac{\sqrt{3}u_{pa}}{2} + \frac{(u_{pb} - u_{pc})}{2\sqrt{3}} \quad (5.13)$$

5.6.4 Evaluation of SPV Instantaneous & DC Loss Components

The solar photovoltaic system's instantaneous compensation term I_{PV} is as follows:

$$I_{PV} = \frac{2P_{PV}}{V_t} \quad (5.14)$$

The proportional and integral (PI) controllers are used to regulate voltage once the fundamental component current of the load has been calculated. A PI controller keeps the voltage of the DC link constant. I_{pdc} signifies the loss component or the current in equation (5.15), the requirement is to keep the DC-link voltage at its reference level.

$$I_{pdc} = K_p(V_{dc}^* - V_{dc}) + K_i \int (V_{dc}^* - V_{dc}) dt \quad (5.15)$$

K_p -Proportional gain, and K_i -Integral gain. It is necessary to extract this loss component from the source.

The DC capacitor will supply the loss component if the source is not strained, causing the DC-link voltage to drop. In this approach, the PI controller gains were determined using the Ziegler-Nichols tuning method, a widely recognized heuristic technique for controller parameter estimation.

5.6.5 CBF-FLL Control System

In conventional grid synchronization schemes, the Frequency Locked Loop (FLL) typically utilizes grid voltage or grid current as its input signal due to the nearly sinusoidal nature of these waveforms under ideal grid conditions. This characteristic enables straightforward extraction of the fundamental frequency and phase angle. Conventional Phase-Locked Loop (PLL) techniques are widely used for grid synchronization due to their simple structure and ease of implementation; however, their performance significantly degrades under distorted grid conditions, voltage imbalance, frequency variations, and weak-grid scenarios, leading to inaccurate phase estimation and poor harmonic immunity. To improve synchronization accuracy, Second-Order Generalized Integrator based Frequency Locked Loop (SOGI-FLL)

methods have been introduced, offering better fundamental component extraction and enhanced harmonic rejection compared to PLLs, particularly under frequency variations. Nevertheless, SOGI-FLL performance deteriorates under severe unbalance and higher-order harmonics. To address this limitation, the Double SOGI-FLL (DSOGI-FLL) structure employs dual orthogonal signal generators, enabling effective positive- and negative-sequence separation and improved performance under unbalanced grid conditions; however, this improvement comes at the cost of increased computational complexity and tuning effort. Alternatively, Least Mean Square-based FLL (LMS-FLL) techniques use adaptive filtering to track grid frequency and phase, providing robustness against noise and parameter variations; yet, LMS-FLLs often suffer from slower convergence and reduced dynamic performance during abrupt grid disturbances. Compared to these methods, advanced synchronization schemes such as Complex Band-Pass Filter-based FLL (CBF-FLL) offer superior harmonic suppression, fast dynamic response, and accurate synchronization under distorted, nonlinear, and weak grid conditions, making them more suitable for modern grid-connected renewable energy systems. The performance comparison of synchronization techniques for grid-connected PV inverters considering harmonic susceptibility, dynamic response, performance under grid distortion, computational complexity and suitability for weak grid scenario is shown in table 5.2 below.

Table 5. 2 Performance comparison of synchronization techniques for grid-connected PV inverters [230]

Technique	Harmonic Susceptibility	Dynamic Response	Performance Under Grid Distortion	Computational Complexity	Suitability for Weak Grid
PLL	Low	Moderate	Poor (sensitive to harmonics and voltage imbalance)	Low	Limited
SOGI-FLL	Moderate	Good	Improved harmonic rejection, limited under severe distortion	Moderate	Moderate
DSOGI-FLL	High	Good	Effective under unbalanced and distorted grids	High	Good
LMS-FLL	High	Slow	Good harmonic suppression, slower convergence	High	Moderate
CBF-FLL (Proposed)	Very High	Fast	Robust under distorted, nonlinear, and weak grid conditions	Moderate	Excellent

From the comparison, it is evident that while DSOGI-FLL and LMS-FLL offer improved harmonic immunity, their higher computational burden and slower convergence limit performance under weak grid conditions. The proposed CBF-FLL provides a balanced solution with fast dynamic response, superior harmonic rejection, and robust synchronization.

However, in the proposed control architecture, the non-linear load current rich in harmonic distortion is employed as the sensed signal for synchronization. This strategic choice stems from the primary control objective of regulating the voltage at the Point of Common Coupling (PCC), even under distorted and dynamic load conditions. It is well established that if the voltage at the PCC is used as the feedback input, the control system tends to regulate the grid current, whereas sensing the current enables voltage regulation [211]. As the proposed system prioritizes voltage stability at the PCC, current sensing is adopted to facilitate closed-loop control and synchronization.

To mitigate the harmonic-rich nature of the non-linear current and accurately extract its fundamental frequency component, a CBF is incorporated within the FLL structure. This integrated CBF-FLL architecture allows robust estimation of the fundamental frequency while effectively suppressing higher-order harmonics and noise components [212-213]. The transfer function of the CBF in the Laplace domain is defined as:

$$CBF(s) = \frac{\omega p}{s - j\omega g + \omega p} \quad (5.16)$$

Where ωp : CBF cutoff frequency (bandwidth) and ωg : Nominal grid angular frequency.

This filter design forms a narrow passband centered around the grid frequency ωg , thereby allowing selective extraction of the fundamental frequency component and significantly improving frequency estimation accuracy in non-ideal environments. The selection of the cut-off frequency ωp introduces a fundamental trade-off between the dynamic response of the FLL and its harmonic suppression capability. Figure 5.5 illustrates the frequency response of the Complex Band-Pass Filter used in the proposed CBF-FLL synchronization scheme for different values of the bandwidth parameter ωp and directly influences the trade-off between harmonic attenuation and dynamic response. Here, ωg represents the grid fundamental angular frequency, centred at which the CBF selectively extracts the fundamental component of the grid voltage/current. The parameter ωp determines the

bandwidth and selectivity of the filter. A lower value of ω_p results in a narrower passband, providing higher harmonic attenuation but slower dynamic response, whereas a higher ω_p widens the passband, enabling faster transient response at the expense of reduced harmonic suppression. The magnitude and phase plots demonstrate that appropriate tuning of ω_p allows an effective trade-off between dynamic performance and harmonic rejection under distorted and weak grid conditions.

Following frequency estimation, the output of the CBF-FLL specifically the β -component is further processed to generate the reference current for the Voltage Source Converter (VSC). The β -component is sampled with alpha part of unit template and then subtracted from the summation of two elements: the PV-side output current I_{pv} and the output of a PI controller responsible for regulating the DC-link voltage. This PI controller minimizes the error between the actual DC voltage V_{dc} and its reference value V_{dc}^* thereby ensuring stable DC-link operation [215].

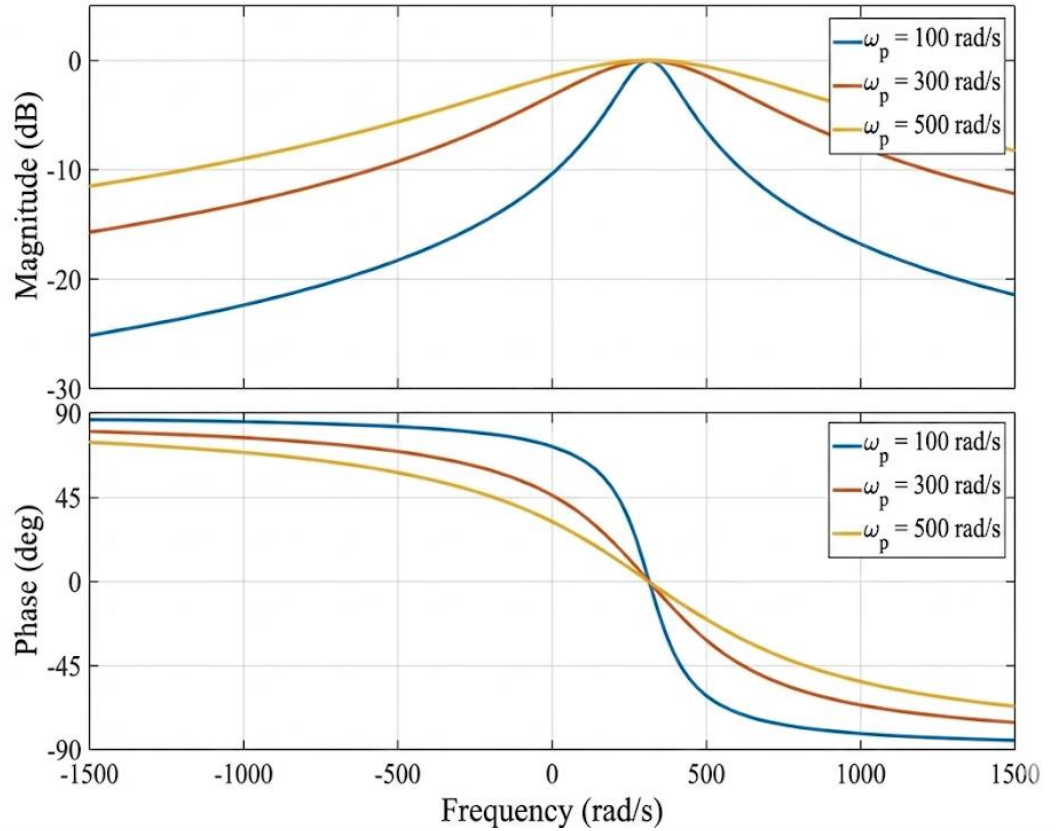


Figure 5.5 Bode Plot of CBF-FLL

The result of this subtraction yields the net current demand to be injected into the grid. To

align this current with the grid voltage phase, the signal is multiplied with the unit templates obtained from the sensed grid voltages. This multiplication ensures that the reference currents are in phase with the fundamental voltage components [216]. To generate gate pulses for VSC, an indirect current control scheme is employed. In this approach, the reference current generated are compared with the actual grid currents and the resulting error is fed into the hysteresis current controller, which maintains the grid current within a predefined hysteresis band [217-220].

5.6.6 Estimation of reference grid current

Every time the quadrature unit template of the grid voltage crossing zero, the load currents' fundamental component ($I_{fp(a,b,c)}$) is sampled and held to derive the fundamental active component of the load current. To estimate the net active power component of the grid current, a sign convention based on the direction of power flow is utilized.

Taking into account the grid current's directions, the PCC's power consumption is attributed to both the load and loss components, hence specified with a positive sign, and the PV array's instantaneous compensation term is a negative sign since the PV array inserts power at the PCC. Thus, the net active power component of the grid current is given in equation (5.13),

$$I_{dT} = I_{PV} + I_{pdc} - I_{fp(a,b,c)} \quad (5.17)$$

The equation used to determine the reference grid currents is given in (5.17) by taking the average of the grid current to balance it.

In-phase reference currents are computed as,

$$i_{ga}^* = \frac{I_{dT}}{3} u_{pa}, \quad i_{gb}^* = \frac{I_{dT}}{3} u_{pb}, \quad i_{gc}^* = \frac{I_{dT}}{3} u_{pc} \quad (5.18)$$

The comparison of reference sensed current and actual current generates a current error signal that is further given to the hysteresis controller for the generation of triggering pulses of VSC. The error current signal is obtained by comparing the generated reference grid currents with the actual grid currents, as shown in equations (5.18). The hysteresis band controller generates the gate signal so that the reference grid current is followed by the actual grid current. To produce the gating pulses required to switch the VSC, hysteresis current controllers (HCCs) are employed in an indirect current control technique.

The error signal of grid current is sent into the HCC, which has a width of 0.01 and is defined as follows:

$$i_{ga}^e = i_{ga}^* - i_{ga}, \quad i_{gb}^e = i_{gb}^* - i_{gb}, \quad i_{gc}^e = i_{gc}^* - i_{gc} \quad (5.19)$$

Where, i_g^* stands the reference grid current and i_g stands the actual grid current.

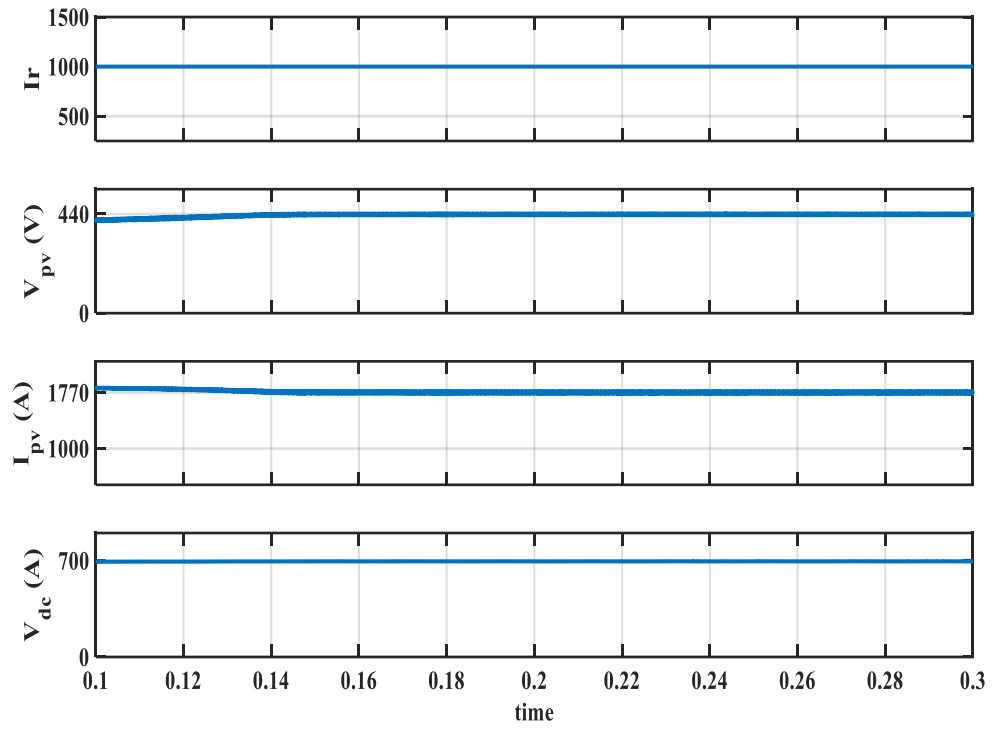
5.7. Simulation Results and Discussion

The proposed double-stage, three-phase grid-connected SPV system is modelled and simulated in MATLAB/Simulink using the SimPowerSystems toolbox. To verify the effectiveness of the developed control strategy, the system is evaluated under a wide range of operating scenarios considering nonlinear load conditions. The performance is further examined during steady-state operation, step changes in irradiance, sudden increases and decreases in load, unbalanced load conditions, and weak-grid scenarios. These test cases collectively demonstrate the robustness of the controller in maintaining voltage stability, ensuring reliable synchronization, and improving overall power quality under practical grid disturbances.

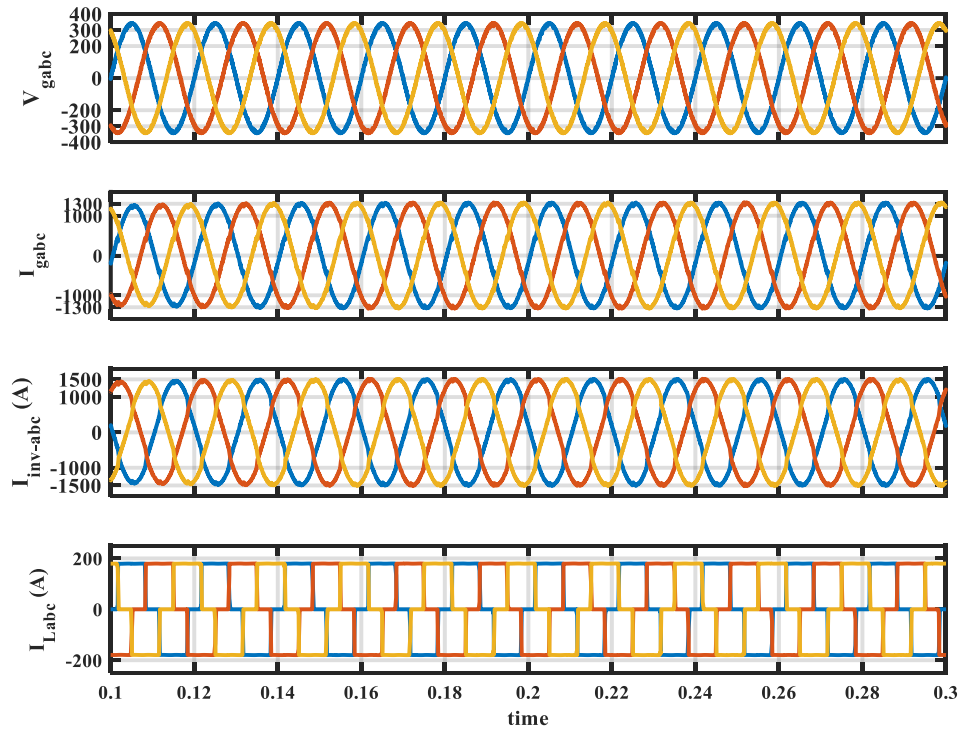
Key electrical parameters observed during the simulation includes grid voltages at PCC (V_{gabc}), grid currents (I_{gabc}), load currents (I_{Labc}), VSC currents ($V_{inv-abc}$), DC-link voltage (V_{dc}), PV array voltage (V_{pv}), PV array current (I_{pv}), and PV power output (P_{pv}). The results demonstrate the system's capability to maintain voltage stability at the PCC, achieve synchronized grid integration, and significantly mitigate harmonic distortion, thereby enhancing the overall power quality and reliability of the distribution network.

5.7.1 Simulation Response Under Steady Condition with Non-linear Load

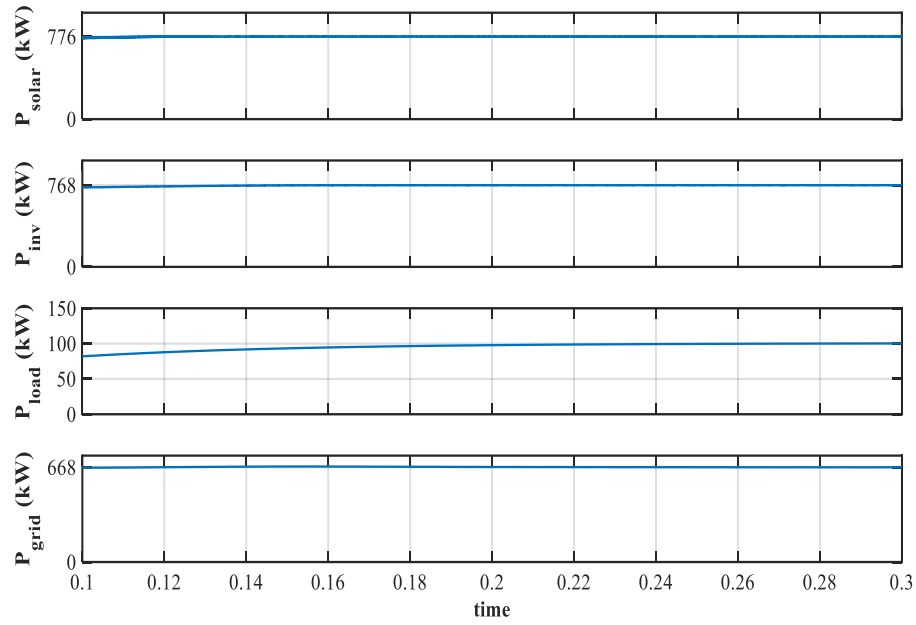
Figure 5.6 (a) shows the steady state response under presence of non-linear load at fixed irradiance of 1000 W/m². The SPV voltage is maintained at its MPP value i.e., 439 V and the DC-link voltage is regulated at 700 V. On the grid side, the injected current 1300 A in grid remains in same phase as that of grid phase voltage 350V maintaining unity power factor as shown in Figure 5.6 (b). The SPV system is capable to produce maximum power of 776 kW, of which it delivers 668 kW to the grid after meeting the demand non-linear load of 100 kW and switching losses of approximate 8 kW as shown in Figure 5.6 (c).



(a)



(b)

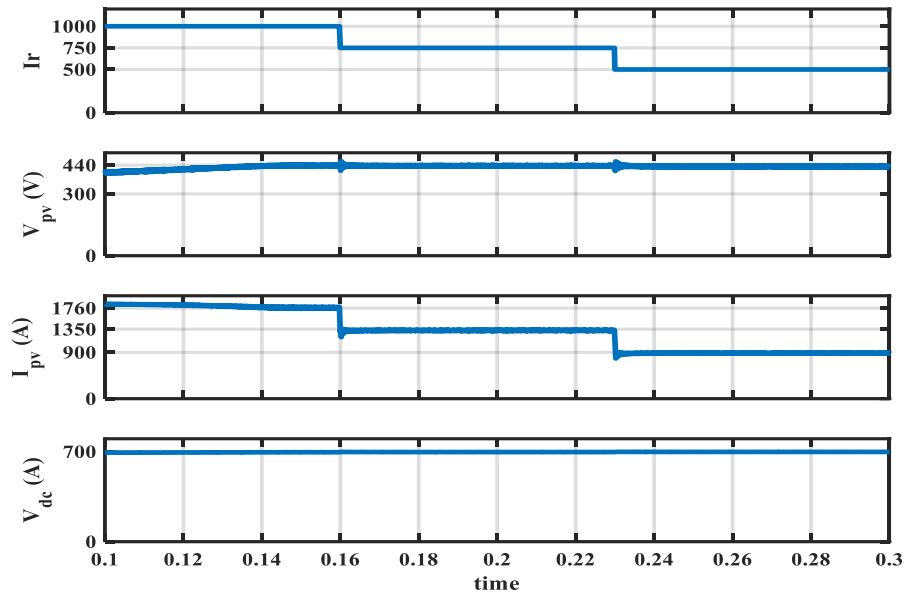


(c)

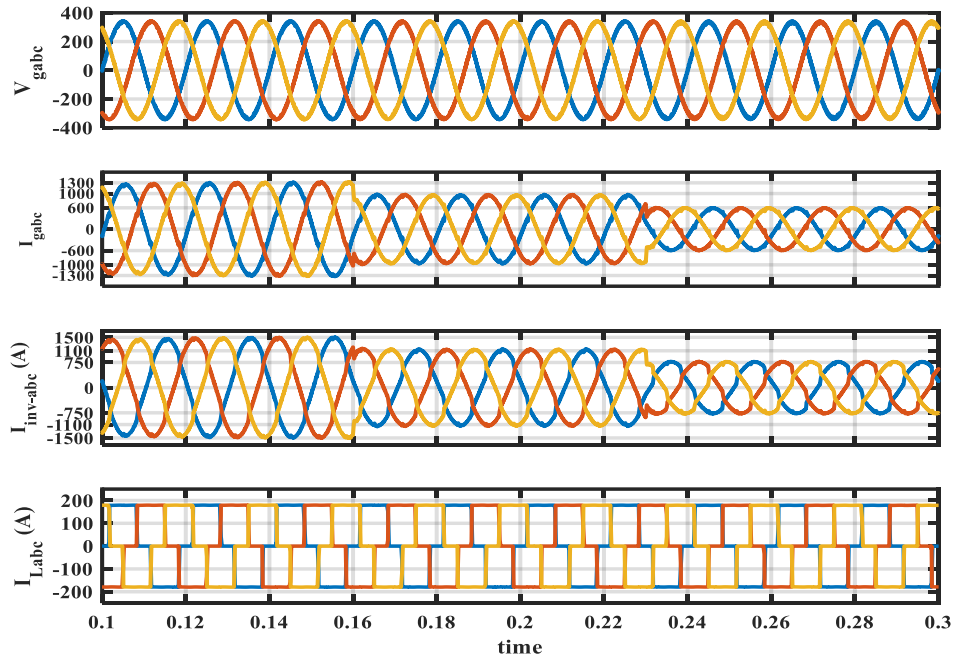
Figure 5. 6 Response under steady state with non-linear load (a) Solar PV parameters (b) Grid and load side waveforms (c) Power balance

5.7.2 Simulation Response Under Change in Irradiance

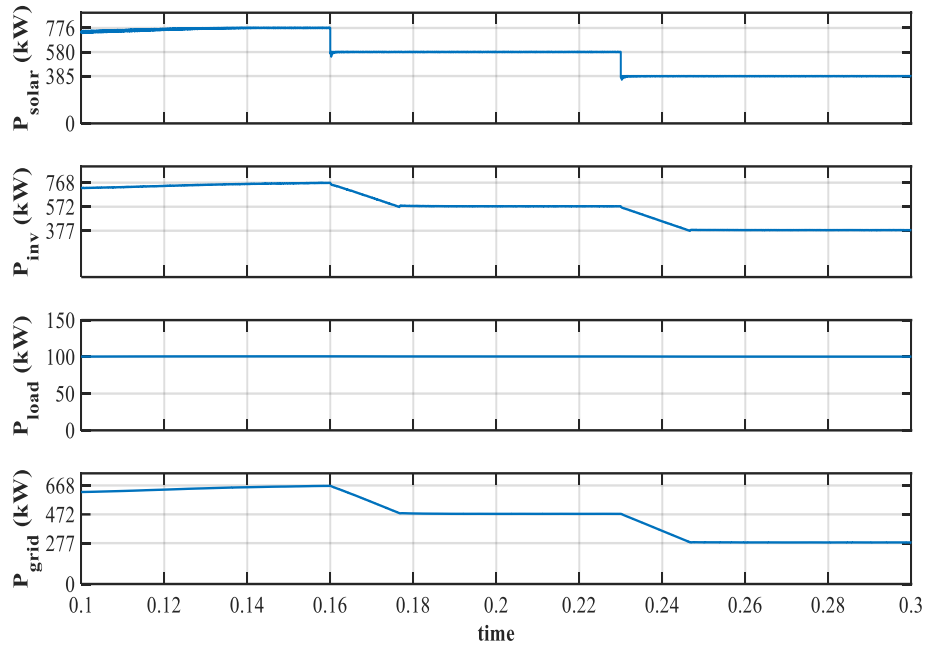
Figure 5.7 (a) shows the system response when solar irradiance decreases from 1000 W/m^2 to 750 W/m^2 at $t = 0.16 \text{ s}$ and to 500 W/m^2 at $t = 0.23 \text{ s}$. The PV voltage remains nearly constant at 440 V , while the PV current reduces from 1760 A to 1345 A and 900 A at $t = 0.16 \text{ s}$ and $t = 0.23 \text{ s}$ respectively. The DC-link voltage is well regulated around 700 V . The grid current decreases proportionally from 1300 A to 1000 A at $t = 0.16 \text{ s}$ to 600 A at $t = 0.23 \text{ s}$. The inverter current follows a similar trend and it decreases from 1490 A to 1200 A at $t = 0.16 \text{ s}$ and to 750 A at $t = 0.23 \text{ s}$, whereas the non-linear load current stays constant at about 195 A , confirming effective control and power balance during irradiance changes maintaining the grid voltage constant by the controller to 350 V as shown in Figure 5.7 (b). The power balance obtained during changing irradiance is shown in Figure 5.7 (c), where solar PV is generating 776 kW at $t = 0 \text{ s}$ at 1000 W/m^2 irradiation condition, at $t = 0.16 \text{ s}$ power reduces to 580 kW as radiations reduces to 750 W/m^2 and at $t = 0.23 \text{ s}$ it further decreases to 385 kW when irradianations are 500 W/m^2 . In same way inverter output power is reduces from 768 kW to 572 kW and it is further reducing to 377 kW at $t = 0.16 \text{ s}$ and $t = 0.23 \text{ s}$ respectively. Considering non-linear load constant to 100 kW , the power fed to grid is decreases from 668 kW to 472 kW and further reduces to 277 kW at $t = 0.16 \text{ s}$ and $t = 0.23 \text{ s}$ respectively as shown in Figure 5.7 (c).



(a)



(b)

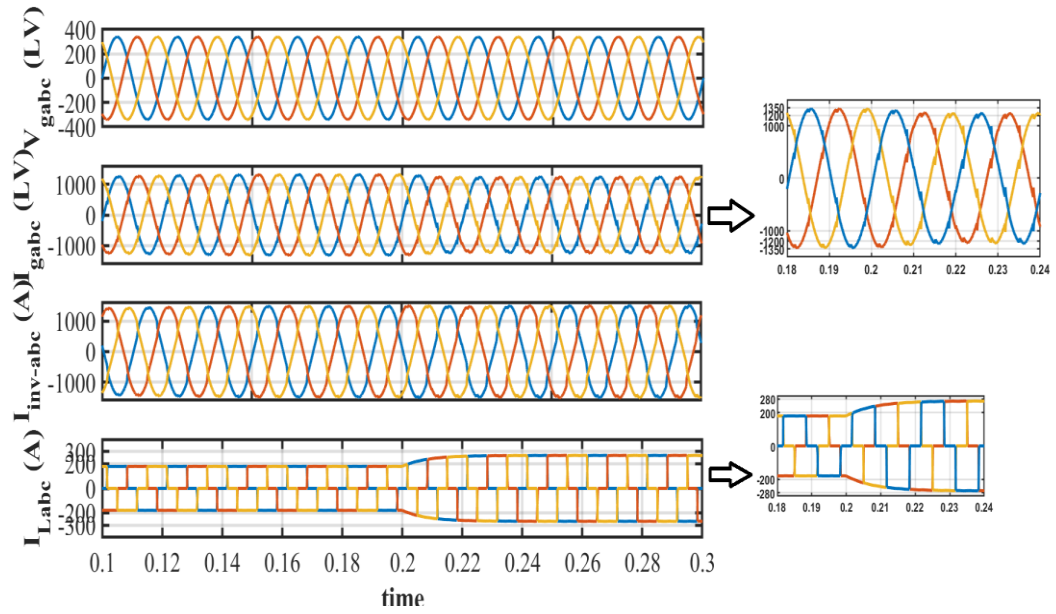


(c)

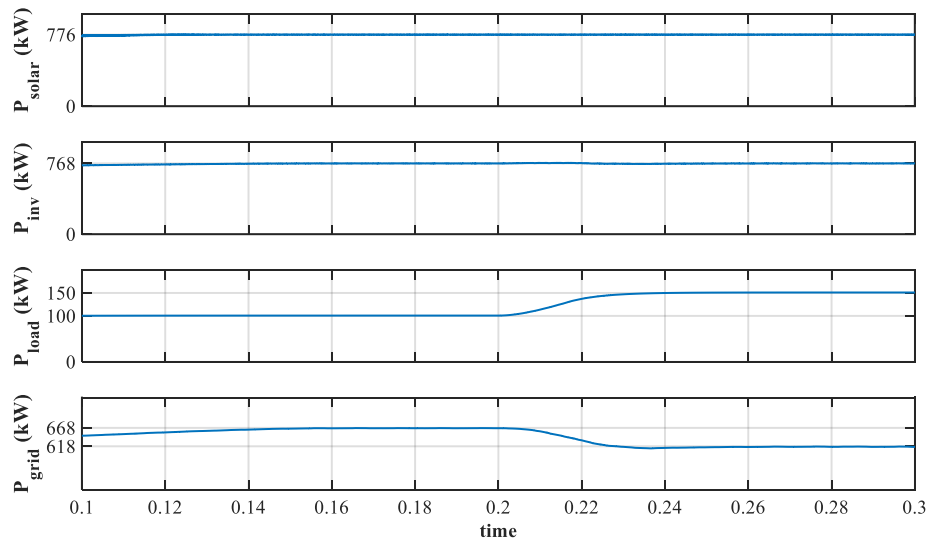
Figure 5.7 Response under varying irradiances with non-linear load (a) Solar PV parameters (b) Grid and load side waveforms (c) Power balance

5.7.3. Simulation Response with Step Increase and Decrease in Non-Linear Load

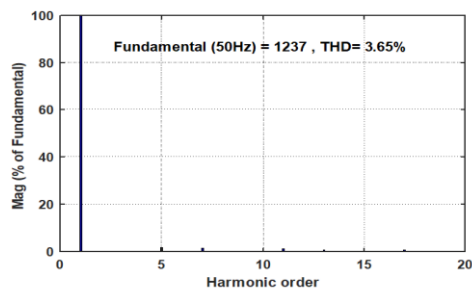
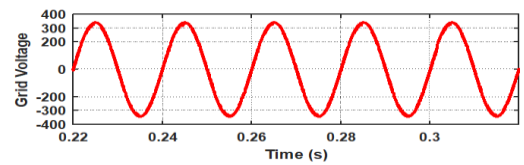
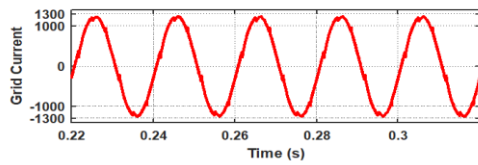
The response observed when the nonlinear load is increased from 100 kW to 150 kW having $R = 2.095 \Omega$ and $L = 50 \text{ mH}$ at $t = 0.2 \text{ s}$. The SPV parameters remain the same i.e irradiation to 1000 W/m^2 and temperature is 25°C . It has been observed that grid current I_{gabc} is 1300 A till 0.2 s. From 0.2 s till 0.3 s, the I_{gabc} is reduces to 1210 A as shown in Figure 5.8 (a). This decreases the active power flow to the grid by 50 kW from 668 kW to 618 kW as shown in Figure 5.8 (b) maintaining the voltage of the system constant. The harmonic spectrum for grid current, grid voltage and non-linear load is as shown in Figure 5.8 (c). It has also been observed that with increase in the loading the grid voltage % THD is 1.80, grid current %THD is 3.65 and non-linear load %THD is 30.18. The grid current and voltage THD remains within the IEEE limits showing the satisfactory operation of controller.



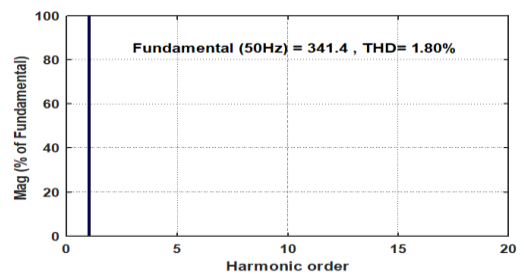
(a)



(b)



Grid Current %THD= 3.65



Grid Voltage %THD= 1.80

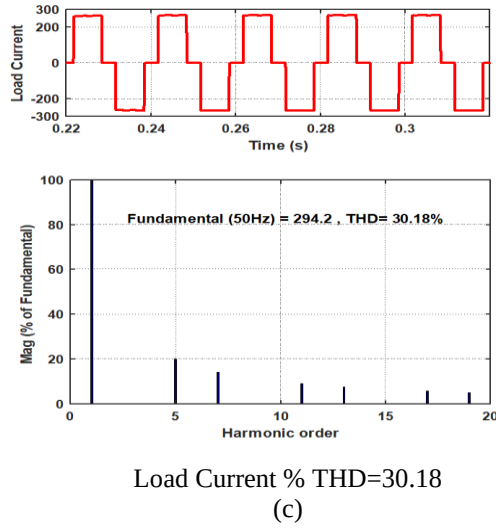
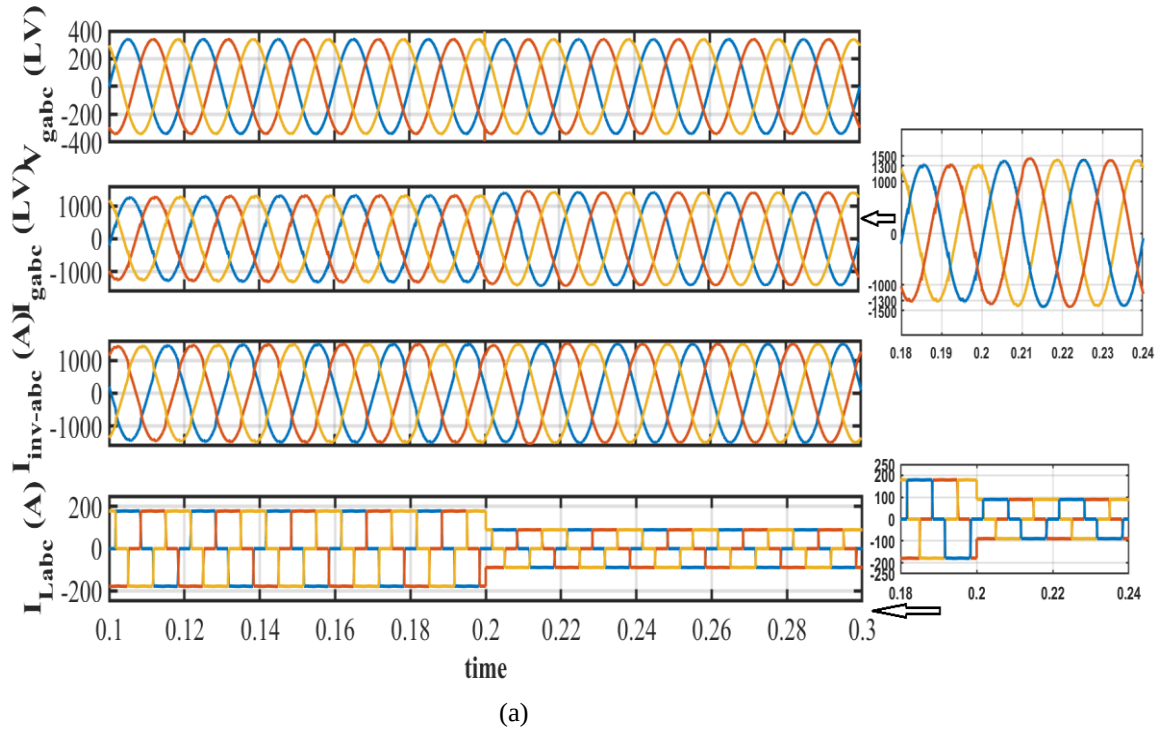
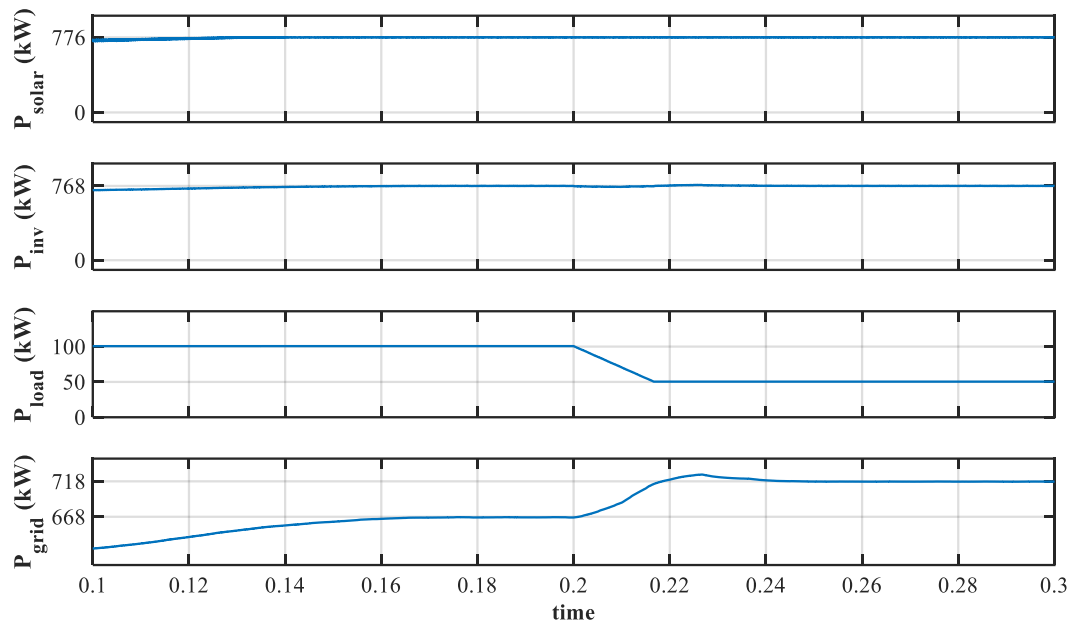


Figure 5.8 Response with step increase in non-linear load (a) Grid and load side waveforms (b) Power balance (c) harmonic spectrum

The response is also observed while decreasing the nonlinear load is from 100 kW to 50 kW having $R = 6.286 \, \Omega$ and $L = 50 \, \text{mH}$ at $t = 0.2 \, \text{s}$. The SPV parameters remain the same i.e irradiation to $1000 \, \text{W/m}^2$ and temperature is 25°C . It has been observed that grid current I_{gabc} is 1300 A till 0.2 s. At $t = 0.2 \, \text{s}$ grid current I_{gabc} is increases to 1450 A as shown in Figure 5.9 (a). This increases the active power flow to the grid by 50 kW from 668 kW to 718 kW as shown in Figure 5.9 (b) maintaining the voltage of the system constant.



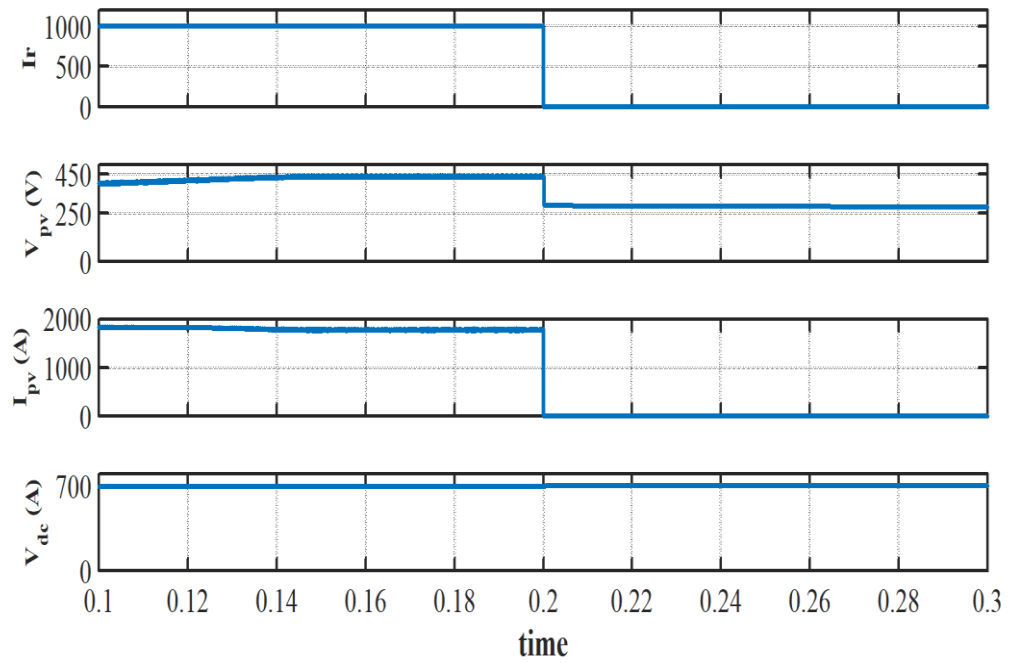


(b)

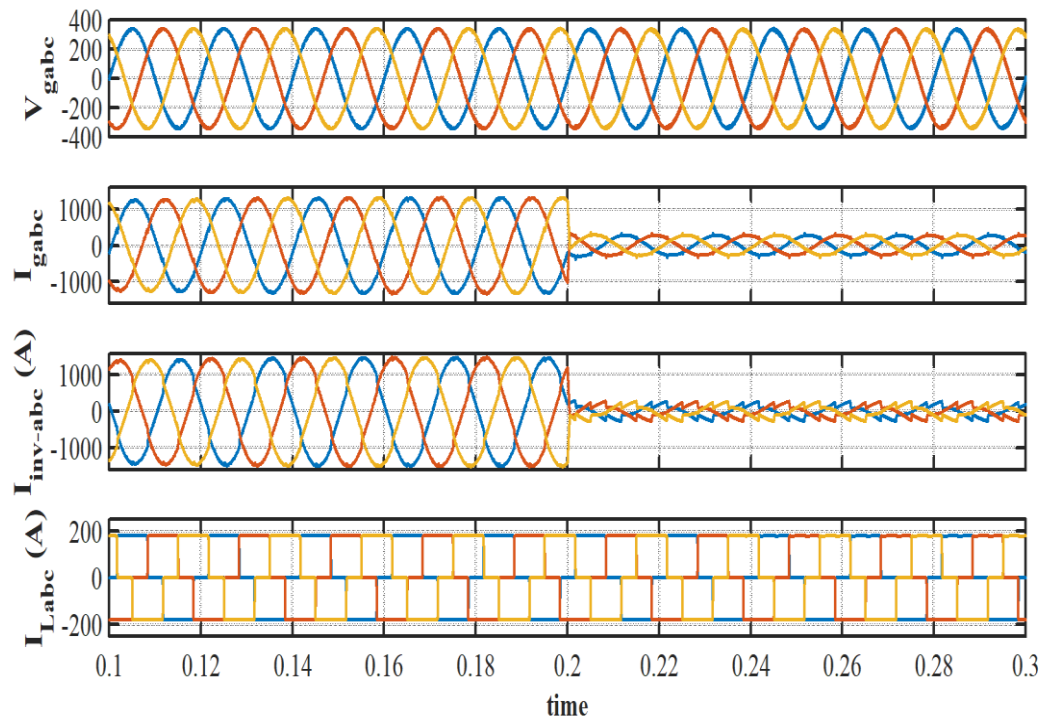
Figure 5.9 Response with step decrease in non-linear load (a) Grid and load side waveforms (b) Power balance

5.7.4. Simulation Response During Night Time or Zero Irradiation.

In the absence of sunlight or zero irradiance, the SPV system generates zero power as the PV current is zero. At this time, the demand at the PCC must be met by the grid. Figure 5.10 (a) shows the required response when irradiance is decreased to 0 at $t = 0.2$ s and the DC-link voltage is maintained constant at 700 V by the VSC. In this case, the grid, instead of absorbing power, now delivers power to the load, which is confirmed by the negative value of grid power as well as the 180° phase shift observed between grid current and grid phase voltage as shown in figure 5.10 (b) and (c). Thus, the control technique is suitable enough to maintain power quality at the PCC.



(a)



(b)

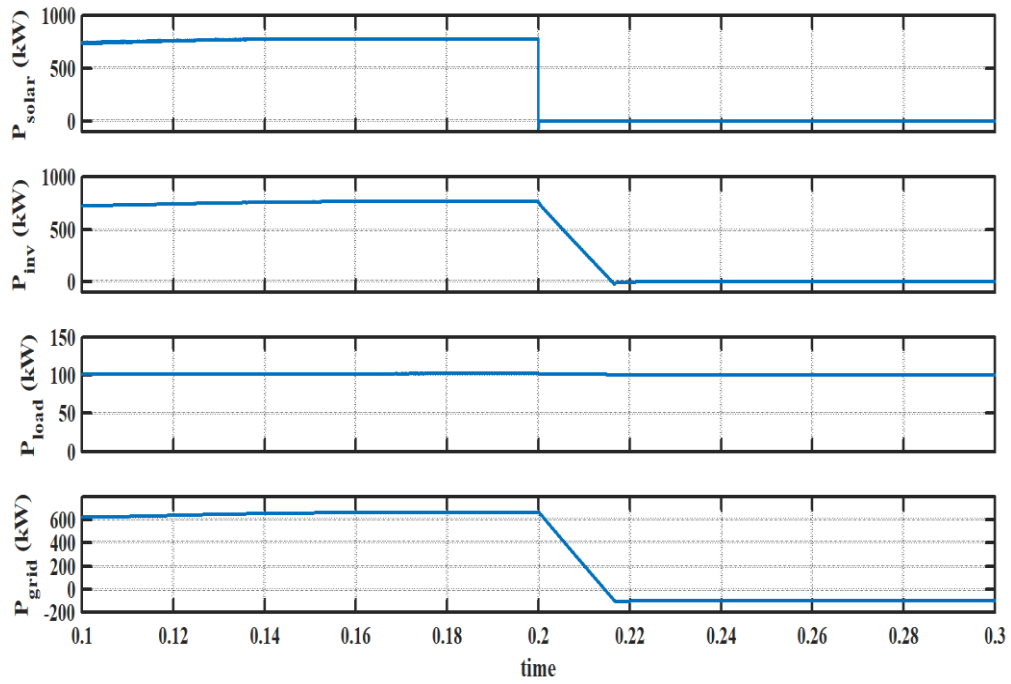
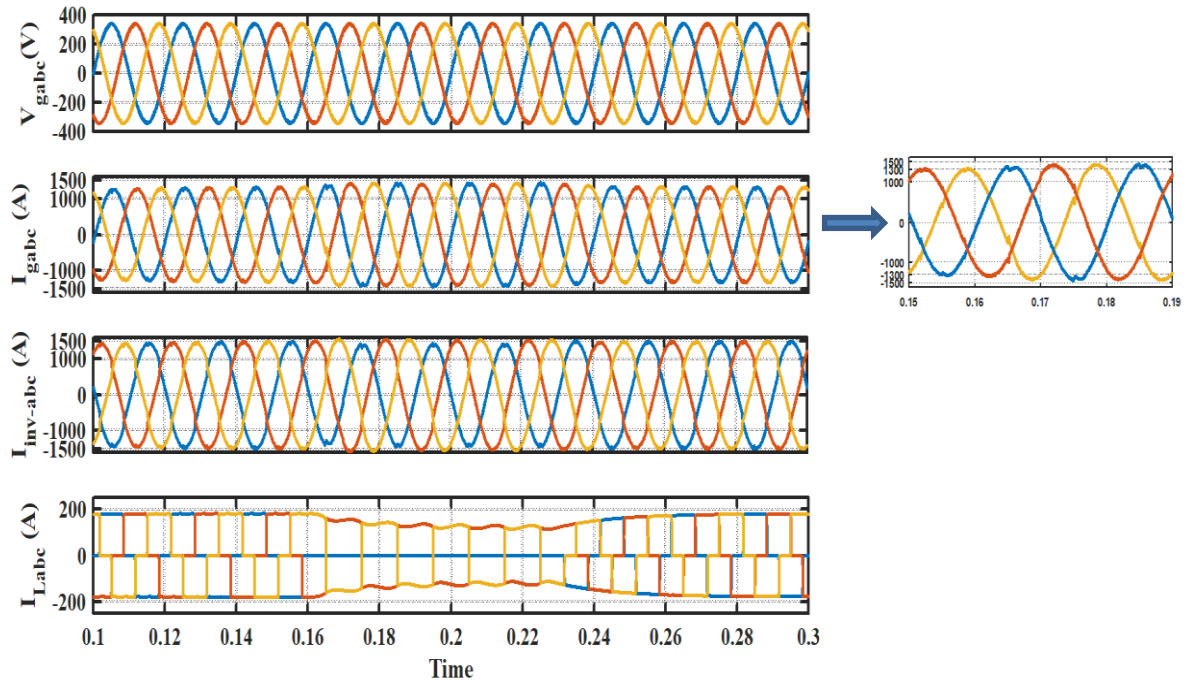


Figure (c)

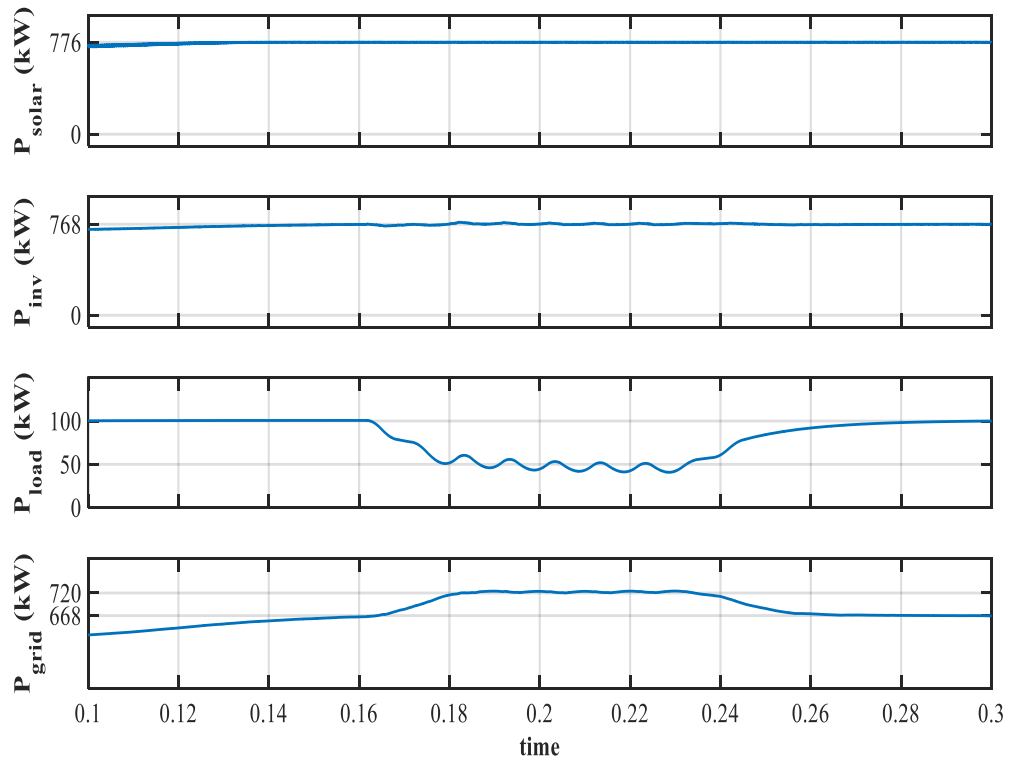
Figure 5.10 Response under zero irradiation (a) Solar PV parameters (b) Grid and load side waveforms (c) Power balance

5.7.5 Unbalancing in Load (One Phase Open)

An R-L load on a diode bridge rectifier of $R = 3.143 \, \Omega$ and $L = 50 \, \text{mH}$ is connected as a nonlinear 3-phase load. When following the elimination of the load from the phase "a", the load situation becomes unbalanced at $t = 0.16 \, \text{s}$ to $t = 0.23 \, \text{s}$ due to the imbalanced load currents as shown in Figure 5.11 (a). Grid current I_{gabc} is approx. 1300 A till $t = 0.16 \, \text{s}$. From $0.16 \, \text{s} - 0.24 \, \text{s}$, I_{gabc} is increases to approximate 1500 A and a little unbalancing is also seen in the inverter current. The VSC generates current in phase "a" to balance the grid current that is 180° out of phase and equal in magnitude to grid current in the phase "a" when the load current decreases to zero in the event of a load imbalance condition. The load and VSC current appear together result in a 3-phase load to the grid that is balanced. The current supply of the grid remains balanced and sinusoidal even in situations where less demand is needed. The 700 V DC-link voltage of the VSC is precisely regulated. Therefore, in the event of a non-linear load unbalancing state, VSC managed by an adaptive control algorithm efficiently performs grid current and voltage balancing and harmonic correction. The solar parameters are kept constant at steady values with $1000 \, \text{W/m}^2$ irradiation and 25°C . The power balance output waveforms are shown in Figure 5.11 (b) where load power is decreases and grid power increases showing access power is feeding to grid during unbalancing period.



(a)



(b)

Figure 5.11 Response under zero irradiation (a) Grid and load side waveforms (b) Power balance

5.7.6 Simulation Response Under Strong and Weak Grid Condition

The stability, dependability, and dynamic behavior of the inverter-grid interface in grid-connected photovoltaic systems is significantly influenced by the grid's strength. The short-circuit ratio (SCR) and grid impedance at the point of common coupling (PCC) are often used to describe grid strength.

High short-circuits capacity, low impedance, and steady voltage and frequency are characteristics of a robust grid. In these circumstances, the grid controls the dynamics of the system, allowing for quick and dependable inverter synchronization with low sensitivity to harmonics or disturbances. Even traditional synchronization techniques work well, and PCC voltage management becomes simpler.

A weak grid, on the other hand, responds to system disturbances with a low SCR, high impedance, and noticeable voltage variations. Weak grids make frequency and phase tracking slower and sometimes unstable because they are more susceptible to harmonics, noise, and imbalanced circumstances. These conditions make it more difficult for the inverter to achieve precise synchronization; PLL/FLL-based algorithms frequently experience oscillations or divergence. The inverter's capacity to control reactive power and maintain voltage stability is much diminished, and the PCC voltage becomes increasingly distorted, particularly in the presence of non-linear loads. For grid-connected PV to operate steadily in this environment, more reliable synchronization and control techniques are required.

To evaluate the robustness of the proposed controller under weak grid conditions, the grid strength is intentionally reduced by reducing the short circuit ratio to 1.5 p.u increasing the value of grid inductance $L=142.8\text{e-}6$ H, and grid resistance $R = 44.9 \text{ m } \Omega$ as grid impedance and the output response of grid voltage and current under weak condition is shown in Figure 5.12 (a) . For strong grid the short circuit ratio is considered as 8 p.u. with $L=1.5\text{e-}6$ H, and $R=1.68 \text{ m } \Omega$ as grid impedance. The response of grid voltage and current under strong grid condition mentioned above is shown in Figure 5.12 (b).

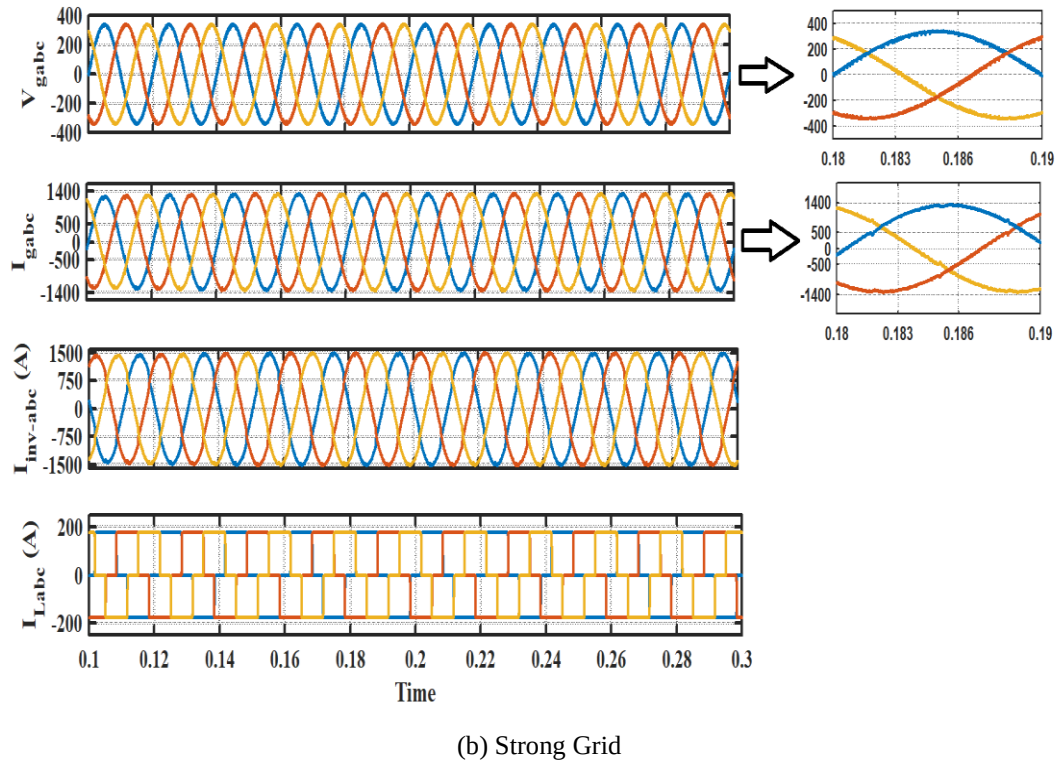
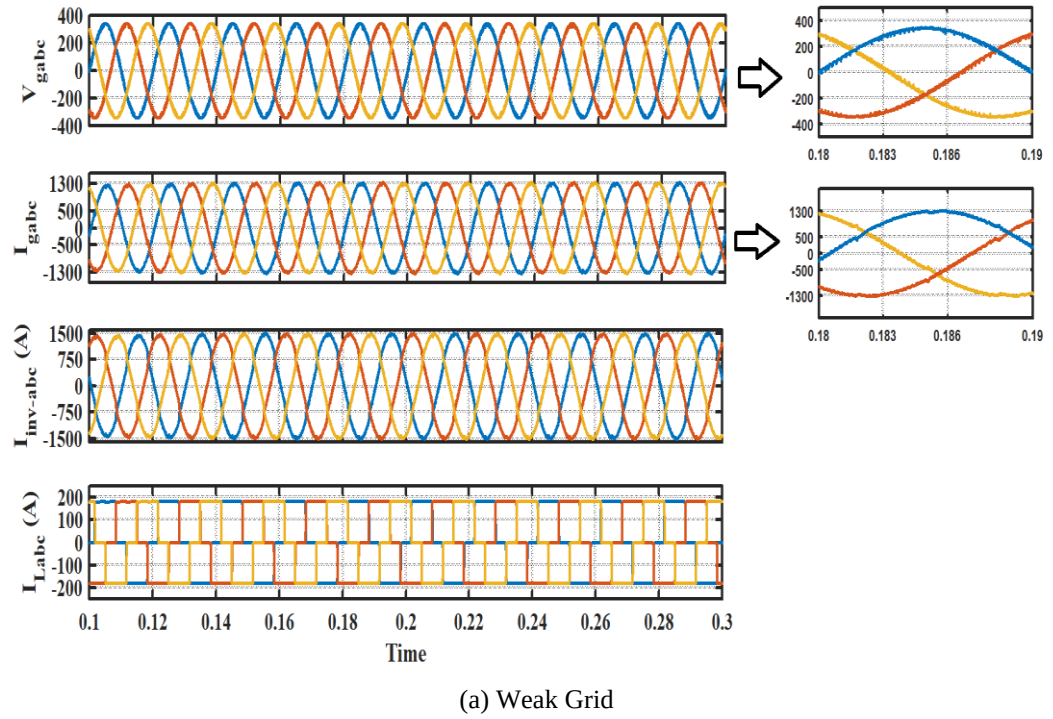
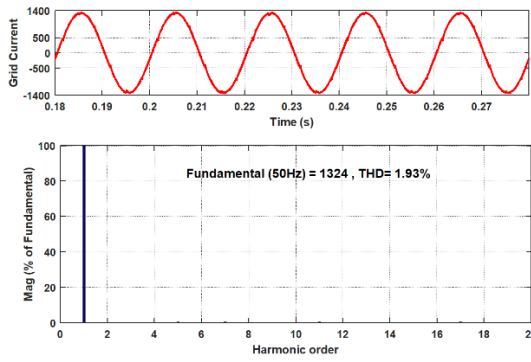
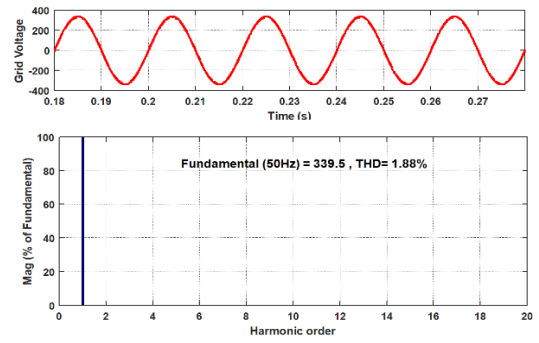


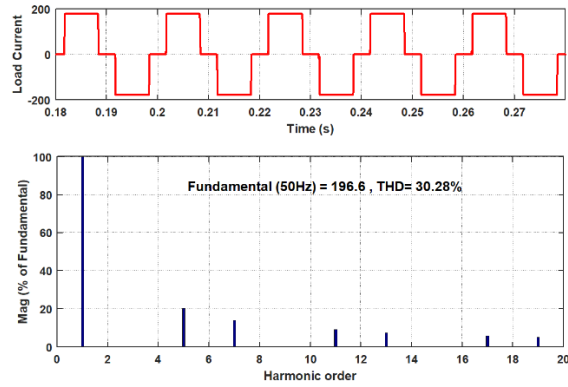
Figure 5.12 Response of grid and load side waveforms under (a) weak grid (b) strong grid condition



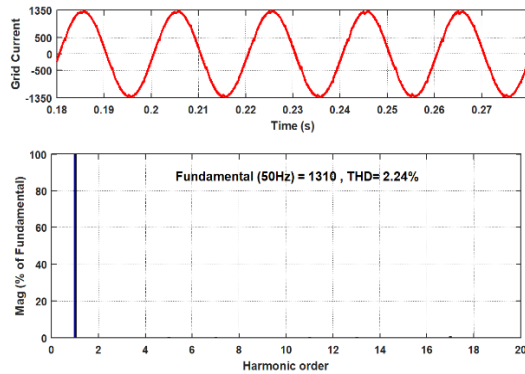
Grid Current %THD= 1.93



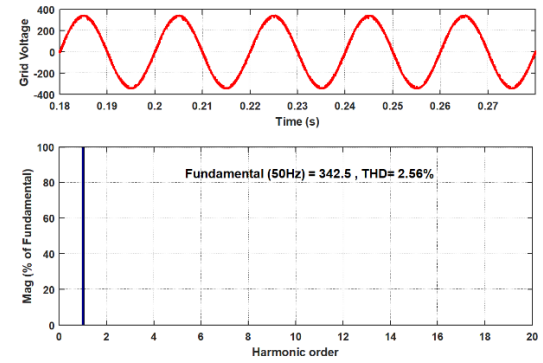
Grid Voltage %THD= 1.88



Load Current %THD= 30.28
(a)



Grid Current %THD= 2.24



Grid Voltage %THD= 2.56

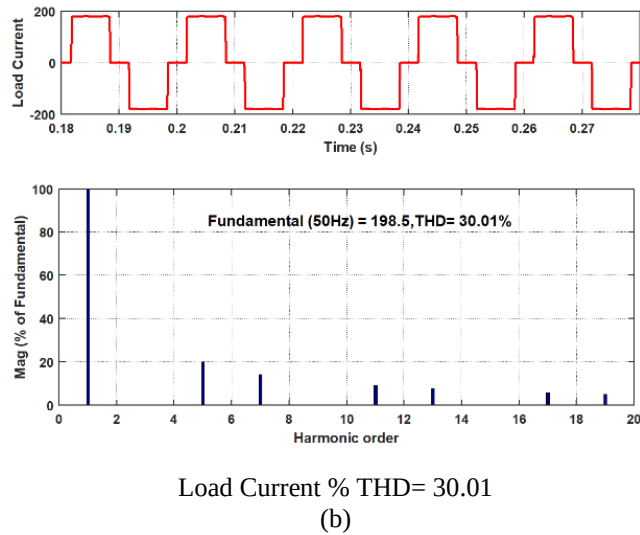


Figure 5.13 Harmonic spectrum under (a)strong grid (b) weak grid

With these stressed conditions, the controller successfully maintains the PCC voltage by keeping THD below 5%, achieving a value of approximately 2.24%, 2.56% for grid current and grid voltage. Load current %THD is 30.01. Figure 5.13 (a) shows the grid voltage, current and load current under strong grid conditions while Figure 5.13 (b) shows the same under weak grid conditions. The proposed CBF-FLL-based synchronization helps mitigate these issues by improving harmonic rejection, immune response to distorted voltage, and enhanced dynamic tracking.

5.8 Comparative Analysis

The DC link voltage (V_{dc}) of CBF-FLL controller is compared with Least mean square (LMS) based FLL as shown in Figure 5.14. Comparative evaluation offers superior dynamic performance, exhibiting a notably shorter DC-link voltage settling time for the same system conditions.

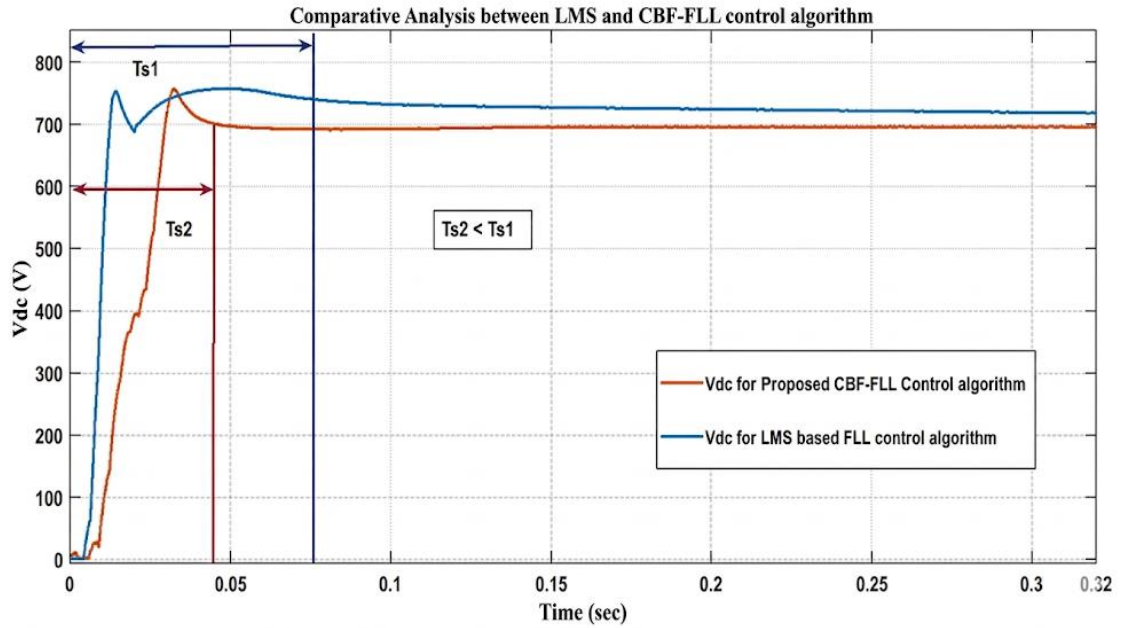


Figure 5.14 Comparative analysis between LMS-FLL and proposed CBF-FLL

The comparative analysis of DC-link (V_{dc}) response between the proposed CBF- FLL controller and the conventional LMS-based FLL, which clearly validates the superior dynamic performance of the proposed approach. It can be observed that the CBF- FLL controller achieves a significantly faster rise and settling of the DC-link voltage, reaching steady-state conditions in a shorter duration (T_{s2}) compared to the LMS-based method (T_{s1}). This reduced settling time indicates improved transient response and faster convergence characteristics of the proposed controller.

Furthermore, the CBF-FLL exhibits minimal overshoot and reduced oscillations during the transient period, ensuring a smoother and more stable DC-link voltage profile. In contrast, the LMS-based FLL shows comparatively slower response and higher settling time, which may affect system stability under rapidly changing operating conditions. The improved performance of the CBF-FLL can be attributed to its efficient frequency tracking capability and enhanced filtering mechanism, which enable accurate extraction of grid parameters even under disturbances and nonlinear loading.

Table 5.3 Dynamic performance comparison of LMS-FLL and proposed CBF-FLL

Performance Metric	LMS-FLL [230-231]	Proposed CBF-FLL
Settling Time (s)	0.078	0.043
Peak Voltage (V)	780	735
Overshoot (%)	8.3	2.1
Steady-State Value (V)	720	720
Grid Current THD (%) Under Strong Grid (High SCR)	2.79	1.93
Grid Current THD (%) Under Weak Grid (Low SCR)	4.1	2.24
Operation Under Weak Grid (Low SCR)	Acceptable but oscillatory	Stable and well damped

The quantitative results summarized in Table 5.3 clearly demonstrate the superior dynamic performance of the proposed CBF-FLL controller over the LMS-FLL method. The DC-link voltage settles in 0.043 s, whereas the LMS-FLL requires 0.078 s, representing an improvement of nearly 45% in transient response speed. Moreover, the peak overshoot is drastically reduced from 8.3% to 2.1%, confirming improved damping and enhanced loop stability.

In addition to faster convergence, the proposed approach significantly enhances power quality. The grid current THD is reduced from 2.79% under LMS-FLL control to approximately 2.24%, well below the 5% limit specified in IEEE-519. This reduction highlights the effectiveness of the complex band-pass filtering stage in isolating the fundamental component while suppressing harmonic distortion under nonlinear loading.

Overall, the numerical evidence verifies that the CBF-FLL achieves faster synchronization, lower overshoot, and improved harmonic mitigation, making it highly suitable for weak-grid and disturbance-prone operating environments.

5.9 Summary

This chapter presented the design and implementation of an advanced Complex Band-Pass Filter-Frequency Locked Loop (CBF-FLL) controller for a grid-connected dual-stage 775 kW solar PV system, aimed at enhancing voltage regulation and power quality at the point of common coupling (PCC) under nonlinear loading conditions. The proposed controller

was rigorously evaluated under various operating scenarios, including fixed and variable irradiance, dynamic load variations, and weak-grid conditions.

The results demonstrate that the CBF-FLL controller ensures stable and accurate grid synchronization, effective voltage regulation, and significant improvement in power quality. The proposed method successfully satisfies IEEE-519 standards, maintaining total harmonic distortion (THD) of grid voltage and current within acceptable limits of 2.56% and 2.24%, respectively. In comparison with the conventional LMS-based FLL approach, the CBF-FLL exhibits superior dynamic performance, achieving a faster DC-link voltage settling time of 0.042 s compared to 0.075 s.

Overall, the CBF-FLL-based control strategy provides a robust, efficient, and reliable solution for the seamless integration of solar PV systems into grid-connected microgrids, particularly under challenging grid conditions.

CHAPTER- 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

This work develops an integrated framework to enhance voltage stability, power quality, and the ability to handle more renewable and EV load in distribution networks with high RES and EVCS penetration, by jointly addressing optimal EVCS siting, optimal renewable generation allocation, and advanced control for voltage and power quality improvement.

- First, a novel hybrid Coati Optimization-Pelican Optimization Algorithm (COA-POA) was developed for optimal EVCS placement in the IEEE 33-bus system, using voltage deviation and VSI as objectives. The hybrid strategy achieved an effective exploration-exploitation balance, ensuring faster convergence and superior solution quality. With optimal siting, the VDI is reduced weak 18th bus from 0.05224 to 0.05082 and VSI at the weak 18th bus improved from 0.23486 to 0.4382, feeder losses decreased from 674.0801 kW to 340.3056 kW, and bus voltages remained within limits under high EV penetration. Compared to random placement, the proposed approach significantly minimizes voltage deviation, enhances VSI, and reduces losses, thereby fulfilling the first research objective.
- Next, the World Cup Optimization (WCO) algorithm was employed to determine the optimal placement of PV and wind generation units in the IEEE-33 bus distribution system. The objective was to enhance the voltage profile, minimize active power losses, and strengthen voltage-stability indices (FVSI, LSI, LSF). Due to critically low voltages at weak buses, coordinated integration of PV and wind units was essential to mitigate the loading impact introduced by EV charging stations (EVCS). Six scenarios were evaluated: (i) base case (ii) Random EVCS placement (iii) optimal EVCS, (iv) PV-EVCS, (v) Wind-EVCS, and (vi) combined PV-Wind-EVCS. It has been observed that optimal PV allocation at Bus 26 improved the minimum system voltage from 0.88575 pu to 0.96814 pu, further increased to 0.97460 pu with wind integration, and ultimately reached 0.97974 pu for the coordinated PV-Wind-EVCS case. Voltage stability indices also showed significant enhancement: FVSI

enhanced from 0.00439 to 0.00328 (optimal EVCS), 0.000507 (PV), 0.000418 (Wind), and 0.000305 (PV-Wind-EVCS). LSI enhanced from 0.053916 (random EVCS) to 0.008365 (PV-Wind-EVCS), while LSF improved from 0.6134695 to 0.176835 across the integrated scenarios. Active power losses reduced from 670.0882 kW to 341.0856 kW (optimal EVCS) and further to 53.6286 kW for the combined PV-Wind-EVCS case. Comparative analysis confirmed that WCO consistently outperformed the conventional PSO algorithm, delivering higher-quality, multi-objective solutions with faster convergence and better global search capability. To ensure robustness and generality, the proposed methodology was additionally validated on the IEEE-69 bus distribution system, where similarly satisfactory improvements were obtained across voltage, losses, and stability indices. This cross-system validation underscores the scalability and reliability of the WCO-based optimization framework.

- The conventional Phase-Locked Loop (PLL) and Frequency Locked Loop (FLL), though widely used for grid synchronization, exhibit limitations under weak grid conditions, nonlinear loads, and renewable intermittency. They often show slower dynamic response, increased oscillations, and reduced frequency tracking accuracy, which negatively impact voltage regulation and power quality. With modern power systems operating under distorted and low-inertia conditions, a more robust and adaptive synchronization technique is required.

A comparative assessment further highlights these limitations. The PLL provides low harmonic immunity and moderate dynamic response but performs poorly under voltage distortion and imbalance, limiting its suitability for weak grids. The SOGI-FLL improves harmonic rejection but remains less effective under severe distortion, while the DSOGI-FLL enhances performance under unbalanced conditions at the cost of higher computational complexity. Similarly, the LMS-FLL offers good harmonic suppression but suffers from slower convergence and higher computational burden. These drawbacks collectively justify the need for an improved control strategy.

Finally, to address these challenges, an advanced Complex Band-Pass Filter-Frequency Locked Loop (CBF-FLL) controller has been developed for a grid-connected dual-stage 775 kW solar PV system. The primary objective of the proposed controller is to enhance voltage regulation and power quality at the point of common coupling (PCC), particularly under nonlinear loading and grid variability. The controller was comprehensively tested under

fixed and variable irradiance conditions, dynamic load variations, and weak grid scenarios to evaluate its robustness and adaptability.

The simulation results demonstrate that the proposed CBF-FLL controller consistently achieves stable synchronization, effective voltage control, and improved power quality. The system complies with IEEE-519 standards, maintaining grid-voltage and grid-current THD at 2.56% and 2.24%, respectively. Furthermore, in comparison with the LMS-based FLL, the proposed method exhibits a significantly faster dynamic response, reducing the DC-link voltage settling time from 0.078 s to 0.043 s. This improvement is also accompanied by reduced overshoot and enhanced damping characteristics, ensuring smoother system operation.

A detailed performance comparison further substantiates the superiority of the proposed approach. The CBF-FLL achieves lower peak voltage (735V compared to 780V), significantly reduced overshoot (2.1% versus 8.3%), and improved harmonic performance under both strong and weak grid conditions. Notably, under weak grid scenarios (low SCR), the proposed controller maintains stable and well-damped operation, whereas the LMS-FLL exhibits oscillatory behaviour.

Overall, the proposed CBF-FLL controller provides a well-coordinated balance between fast dynamic response, high harmonic immunity, moderate computational complexity, and robust performance under distorted and weak grid conditions. These features make it a highly effective and reliable solution for the seamless integration of solar PV systems into modern grid-connected microgrids, thereby addressing critical challenges associated with renewable-rich power systems.

6.2. Scope of the Future Work

- Future research can extend this work by incorporating techno-economic objectives such as investment cost, operating cost, and tariff structures, as emphasized in recent literature.
- Uncertainty-aware and probabilistic optimization can be adopted to address stochastic EV charging demand and renewable generation variability.
- The framework may be expanded to include fast and ultra-fast EV chargers, V2G operation, and market-oriented models.
- Validation on large-scale and practical distribution networks, along with real-time, adaptive optimization.
- Advanced inverter control features such as grid-code compliance and fault ride-through and hardware-in-the-loop implementation, will further enhance practical applicability. can also be explored.
- Further investigation into advanced control methodologies, including machine learning-based approaches and model predictive control, to enhance performance under dynamic solar and wind conditions.
- The incorporation of energy storage technologies, notably batteries and supercapacitors, serves to augment system reliability and mitigate the challenges associated with fluctuating renewable power generation.

REFERENCES

- [1] Hatziaargyriou, Nikos, et al. "Definition and classification of power system stability–revisited & extended." *IEEE Transactions on Power Systems* 36.4 (2020): 3271-3281.
- [2] Kundur, Prabha, et al. "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions." *IEEE transactions on Power Systems* 19.3 (2004): 1387-1401.
- [3] Mousavi, O. Alizadeh, Mokhtar Bozorg, and Rachid Cherkaoui. "Preventive reactive power management for improving voltage stability margin." *Electric Power Systems Research* 96 (2013): 36-46.
- [4] Andersson, Göran, et al. "Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance." *IEEE transactions on Power Systems* 20.4 (2005): 1922-1928.
- [5] Eremia, Mircea, and Mohammad Shahidehpour, eds. *Handbook of electrical power system dynamics: modeling, stability, and control*. John Wiley & Sons, 2013.
- [6] Taylor, Carson W. "Voltage stability." *Power system voltage stability* (1994): 27-32.
- [7] Lu, Wei, et al. "Blackouts: Description, analysis and classification." *WSEAS International Conference on Power Systems*. 2006.
- [8] Bo, Zeng, et al. "An analysis of previous blackouts in the world: Lessons for China' s power industry." *Renewable and Sustainable Energy Reviews* 42 (2015): 1151-1163.
- [9] Veloza, Olga P., and Francisco Santamaria. "Analysis of major blackouts from 2003 to 2015: Classification of incidents and review of main causes." *The Electricity Journal* 29.7 (2016): 42-49.
- [10] Pereira, Rita Manuela Monteiro, Carlos Manuel Machado Ferreira, and Fernando Maciel Barbosa. "Comparative study of STATCOM and SVC performance on dynamic voltage collapse of an electric power system with wind generation." *IEEE Latin America Transactions* 12.2 (2014): 138-145.
- [11] Kundur, Prabha. "Power system stability." *Power system stability and control* 10.1 (2007): 7-1.
- [12] Van Cutsem, Thierry, and Costas Vournas. *Voltage stability of electric power systems*. Springer Science & Business Media, 2007.
- [13] Panchal, A. K. "Voltage stability of a large grid." *2005 International Power Engineering Conference*. IEEE, 2005.
- [14] Tang, Junjie, et al. "Adaptive load shedding based on combined frequency and voltage stability assessment using synchrophasor measurements." *IEEE Transactions on power systems* 28.2 (2013): 2035-2047.
- [15] Tang, Junjie, et al. "Adaptive load shedding based on combined frequency and voltage stability assessment using synchrophasor measurements." *IEEE Transactions on power systems* 28.2 (2013): 2035-2047.

REFERENCES

- [16] Sasikala, J., and M. Ramaswamy. "Fuzzy based load shedding strategies for avoiding voltage collapse." *Applied Soft Computing* 11.3 (2011): 3179-3185.
- [17] Huang, Garng M., and N-KC Nair. "Detection of dynamic voltage collapse." *IEEE Power Engineering Society Summer Meeting*, Vol. 3. IEEE, 2002.
- [18] Nizam, Muhammad, Azah Mohamed, and Aini Hussain. "Performance evaluation of voltage stability indices for dynamic voltage collapse prediction." *Journal of Applied Science* 6.5 (2006): 1104-1113.
- [19] Abhyankar, S. G., and A. J. Flueck. "A new confirmation of voltage collapse via instantaneous time domain simulation." *41st North American Power Symposium*. IEEE, 2009.
- [20] Cupelli, Marco, C. Doig Cardet, and Antonello Monti. "Comparison of line voltage stability indices using dynamic real time simulation." *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*. IEEE, 2012.
- [21] Viral, Rajkumar, and Dheeraj Kumar Khatod. "Optimal planning of distributed generation systems in distribution system: A review." *Renewable and sustainable energy Reviews* 16.7 (2012): 5146-5165.
- [22] Viral, Rajkumar, and D. Kumar Khatod. "An analytical approach for sizing and siting of DGs in balanced radial distribution networks for loss minimization." *International Journal of Electrical Power & Energy Systems* 67 (2015): 191-201.
- [23] Kayal, Partha, and C. K. Chanda. "Placement of wind and solar based DGs in distribution system for power loss minimization and voltage stability improvement." *International Journal of Electrical Power & Energy Systems* 53 (2013): 795-809.
- [24] Olivares, Daniel E., et al. "Trends in microgrid control." *IEEE Transactions on smart grid* 5.4 (2014): 1905-1919.
- [25] Aththanayake, Lahiru, et al. "Challenges to voltage and frequency stability of microgrids under renewable integration." *2020 Australasian Universities Power Engineering Conference (AUPEC)*. IEEE, 2020.
- [26] Adetokun, Bukola B., Christopher M. Muriithi, and Joseph O. Ojo. "Voltage stability assessment and enhancement of power grid with increasing wind energy penetration." *International Journal of Electrical Power & Energy Systems* 120 (2020): 105988.
- [27] Chen, Ziyu, et al. "A simplified method for voltage stability analysis of wind power integration." *2018 International Conference on Power System Technology (POWERCON)*. IEEE, 2018.
- [28] A. Petean-Pina, C. Opathella, and B. Venkatesh, "Effect of Wind Generation Uncertainty on Voltage Stability - A Singular Value Analysis," *2018 IEEE Electrical Power and Energy Conference (EPEC)*, pp. 1–7, 2018.
- [29] S. Nikkhah and A. Rabiee, "Optimal wind power generation investment, considering voltage stability of power systems," *Renewable Energy*, vol. 115, pp. 308–325, 2018.
- [30] S. Kumar, A. Kumar, and N. Sharma, "A novel method to investigate voltage stability of IEEE-14 bus wind integrated system using PSAT," *Frontiers in Energy*, vol. 14, pp. 410–418, 2020.

REFERENCES

- [31] Qin, Boyu, et al. "Quantitative short-term voltage stability analysis of power systems integrated with DFIG-based wind farms." *IET Generation, Transmission & Distribution* 14.19 (2020): 4264-4272.
- [32] Ghaffarianfar, Majid, and Amin Hajizadeh. "Voltage stability of low-voltage distribution grid with high penetration of photovoltaic power units." *Energies* 11.8 (2018): 1960.
- [33] Hammad, Mohammad, and Ahmad Harb. "Static analysis for voltage stability of the Northern Jordanian power system." *2018 9th International Renewable Energy Congress (IREC)*. IEEE, 2018.
- [34] Song, Yue, David J. Hill, and Tao Liu. "Static voltage stability analysis of distribution systems based on network-load admittance ratio." *IEEE Transactions on Power Systems* 34.3 (2018): 2270-2280.
- [35] Muhammed, Abdullahi Oboh, and Muhyaddin Rawa. "A systematic PVQV-curves approach for investigating the impact of solar photovoltaic-generator in power system using powerworld simulator." *Energies* 13.10 (2020): 2662.
- [36] Rahman, Sharmin, et al. "Analysis of power grid voltage stability with high penetration of solar PV systems." *IEEE Transactions on Industry Applications* 57.3 (2021): 2245-2257.
- [37] Xu, Xiaoyuan, et al. "Power system voltage stability evaluation considering renewable energy with correlated variabilities." *IEEE Transactions on Power Systems* 33.3 (2017): 3236-3245.
- [38] Parihar, Shradha S., and Nitin Malik. "Optimal allocation of renewable DGs in a radial distribution system based on new voltage stability index." *International Transactions on Electrical Energy Systems* 30.4 (2020): e12295.
- [39] Gumilar, Langlang, et al. "Analysis voltage stability in the interconnection of battery charging station and renewable energy." *2020 2nd International Conference on Cybernetics and Intelligent System (ICORIS)*. IEEE, 2020.
- [40] Shuai, Chu, et al. "Global sensitivity analysis of voltage stability in the power system with correlated renewable energy." *Electric Power Systems Research* 192 (2021): 106916.
- [41] Xia, Chengjun, et al. "Probability analysis of steady-state voltage stability considering correlated stochastic variables." *International Journal of Electrical Power & Energy Systems* 131 (2021): 107105.
- [42] Xue, Ancheng, et al. "A new quantitative analysis method for overvoltage in sending end electric power system with UHVDC." *IEEE Access* 8 (2020): 145898-145908.
- [43] Serem, Noah, Lawrence K. Letting, and Josiah Munda. "Voltage profile and sensitivity analysis for a grid connected solar, wind and small hydro hybrid system." *Energies* 14.12 (2021): 3555.
- [44] Hemmatpour, Mohammad Hasan, Mohsen Mohammadian, and Ali-Akbar Gharaveisi. "Simple and efficient method for steady-state voltage stability analysis of islanded microgrids with considering wind turbine generation and frequency deviation." *IET Generation, Transmission & Distribution* 10.7 (2016): 1691-1702.
- [45] da Silva Neto, João Alves, Eliane Valença Nascimento de Lorenci, and Antonio Carlos Zambroni de Souza. "Voltage stability analysis using energy function considering the transmission-

REFERENCES

- microgrid coupling and microgrid operation in islanded mode." *2020 International Conference on Power, Instrumentation, Control and Computing (PICC)*. IEEE, 2020.
- [46] Micky, R. Rohikaa, et al. "Assessment of voltage stability in microgrid." *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*. IEEE, 2016.
 - [47] Kanojia, Sarika, and Bhavik N. Suthar. "Voltage Stability Analysis in Modern Power System Considering Wind Energy Conversion System," *2023 IEEE IAS Global Conference on Emerging Technologies (GlobConET)*. IEEE, 2023.
 - [48] Pérez-Londoño, S., L. F. Rodríguez, and G. Olivar. "A simplified voltage stability index (SVSI)." *International Journal of Electrical Power & Energy Systems* 63 (2014): 806-813.
 - [49] Matavalam, Amarsagar Reddy Ramapuram, and Venkataramana Ajjarapu. "Calculating the long term voltage stability margin using a linear index." *2015 IEEE Power & Energy Society General Meeting*. IEEE, 2015.
 - [50] Simpson-Porco, John William, and Francesco Bullo. "Distributed monitoring of voltage collapse sensitivity indices." *IEEE Transactions on Smart Grid* 7.4 (2016): 1979-1988.
 - [51] Kamel, Mariana, Abdelrahman A. Karrar, and Ahmed H. Eltom. "Development and application of a new voltage stability index for on-line monitoring and shedding." *IEEE Transactions on power systems* 33.2 (2017): 1231-1241.
 - [52] Canizares, Claudio A. "Voltage stability assessment: concepts, practices and tools." *IEEE/PES power system stability subcommittee special publication SP101PSS* (2002).
 - [53] Fink, L. H. *Bulk power system voltage phenomena: Voltage stability and security: Proceedings*. No. EPRI-EL-6183; CONF-880981-. Electric Power Research Inst., Palo Alto, CA (USA); Carlsen and Fink Associates, Inc., Fairfax, VA (USA), 1988.
 - [54] Deng, Guiping, Yuanzhan Sun, and Jian Xu. "A new index of voltage stability considering distribution network." *2009 Asia-Pacific Power and Energy Engineering Conference*. IEEE, 2009.
 - [55] Suzuki, Mamoru, et al. "Newly developed voltage security monitoring system." *IEEE Transactions on Power systems* 7.3 (2002): 965-973.
 - [56] Ajjarapu, Venkataramana, and Colin Christy. "The continuation power flow: a tool for steady state voltage stability analysis." *IEEE transactions on Power Systems* 7.1 (2002): 416-423.
 - [57] Yorino, Naoto, Shigemi Harada, and Haozhong Cheng. "A method to approximate a closest loadability limit using multiple load flow solutions." *IEEE Transactions on Power Systems* 12.1 (1997): 424-429.
 - [58] DeMarco, Christopher L. "A new method of constructing Lyapunov functions for power systems." *1988., IEEE International Symposium on Circuits and Systems*. IEEE, 1988.
 - [59] Overbye, Thomas J., and Christopher L. De Marco. "Voltage security enhancement using energy-based sensitivities." *IEEE Transactions on Power Systems* 6.3 (1991): 1196-1202.
 - [60] Venikov, V. A., et al. "Estimation of electrical power system steady-state stability in load flow calculations." *IEEE Transactions on Power Apparatus and Systems* 94.3 (2006): 1034-1041.
 - [61] Lof, P-A., et al. "Fast calculation of a voltage stability index." *IEEE Transactions on power systems* 7.1 (1992): 54-64.

REFERENCES

- [62] Gao, Baofu, G. Kip Morison, and Prabhashankar Kundur. "Voltage stability evaluation using modal analysis." *IEEE transactions on power systems* 7.4 (2002): 1529-1542.
- [63] Li, Yaran, et al. "Assessment and enhancement of static voltage stability with inverter-based generators." *IEEE Transactions on Power Systems* 36.3 (2021): 2737-2740.
- [64] Obadina, O. O., and G. J. Berg. "Identifying electrically weak and strong segments of a power system from a voltage stability viewpoint." *IEE Proceedings C (Generation, Transmission and Distribution)*. Vol. 137. No. 3. IEE, 1990.
- [65] Flatabo, N., R. Ognedal, and T. Carlsen. "Voltage stability condition in a power transmission system calculated by sensitivity methods." *IEEE Transactions on Power Systems* 5.4 (1990): 1286-1293.
- [66] Berizzi, Alberto, et al. "First and second order methods for voltage collapse assessment and security enhancement." *IEEE Transactions on Power Systems* 13.2 (1998): 543-551.
- [67] Wang, Liancheng, and Adly A. Girgis. "On-line detection of power system small disturbance voltage instability." *IEEE transactions on power systems* 11.3 (1996): 1304-1313.
- [68] Da Silva, AM Leite, et al. "Voltage collapse risk assessment." *Electric Power Systems Research* 54.3 (2000): 221-227.
- [69] Chiang, Hsiao-Dong, and Rene Jean-Jumeau. "Toward a practical performance index for predicting voltage collapse in electric power systems." *IEEE Transactions on power systems* 10.2 (1995): 584-592.
- [70] Mohamed, A., G. B. Jasmon, and S. Yusoff. "A static voltage collapse indicator using line stability factors." *Journal of industrial technology* 7.1 (1989): 73-85.
- [71] Rahman, TK Abdul, and G. B. Jasmon. "A new technique for voltage stability analysis in a power system and improved loadflow algorithm for distribution network." *Proceedings 1995 International Conference on Energy Management and Power Delivery EMPD'95*. Vol. 2. IEEE, 1995.
- [72] Gubina, Ferdinand, and B. Strmcnik. "Voltage collapse proximity index determination using voltage phasors approach." *IEEE transactions on power systems* 10.2 (1995): 788-794.
- [73] Moghavvemi, Mahmoud, and F. M. Omar. "Technique for contingency monitoring and voltage collapse prediction." *IEE Proceedings-Generation, Transmission and Distribution* 145.6 (1998): 634-640.
- [74] Ratra, Saurabh, Rajive Tiwari, and Khaleequr Rehman Niazi. "Voltage stability assessment in power systems using line voltage stability index." *Computers & Electrical Engineering* 70 (2018): 199-211.
- [75] Moghavvemi, M., and M. O. Faruque. "Technique for assessment of voltage stability in ill-conditioned radial distribution network." *IEEE Power Engineering Review* 21.1 (2001): 58-60.
- [76] Musirin, Ismail, and TK Abdul Rahman. "Novel fast voltage stability index (FVSI) for voltage stability analysis in power transmission system." *Student conference on research and development*. IEEE, 2002.

REFERENCES

- [77] Albuquerque, Mário A., and Carlos A. Castro. "A contingency ranking method for voltage stability in real time operation of power systems." *2003 IEEE Bologna Power Tech Conference Proceedings*, Vol. 1. IEEE, 2003.
- [78] Milosevic, Borka, and Miroslav Begovic. "Voltage-stability protection and control using a wide-area network of phasor measurements." *IEEE Transactions on Power Systems* 18.1 (2003): 121-127.
- [79] He, Tan, S. Kolluri, S. Mandal, F. Galvan, and P. Rasigoufar. "Identification of weak locations in bulk transmission systems using voltage stability margin index." *IEEE Power Engineering Society General Meeting* (2004): 1814-1819.
- [80] Nizam, Muhammad, Azah Mohamed, and Aini Hussain. "Dynamic voltage collapse prediction in power systems using power transfer stability index." *IEEE International Power and Energy Conference* (2006): 246-250.
- [81] Yazdanpanah-Goharrizi, Ali, and Reza Asghari. "A novel line stability index (NLSI) for voltage stability assessment of power systems." *7th WjSEAS International Conference on Power Systems, Beijing, China* (2007): 164-167.
- [82] Subramani, Chinnamuthu, Subhransu Dash, M. Alamelu Bhaskar, M. Jagadeeshkumar, K. Sureshkumar, and R. Parthipan. "Line outage contingency screening and ranking for voltage stability assessment." *IEEE International Conference on Power Systems* (2009): 1-5.
- [83] Tiwari, Rajive, K. R. Niazi, and Vikas Gupta. "Line collapse proximity index for prediction of voltage collapse in power systems." *International Journal of Electrical Power & Energy Systems* 41.1 (2012): 105-111.
- [84] Kanimozhi, R., and K. Selvi. "A novel line stability index for voltage stability analysis and contingency ranking in power system using fuzzy based load flow." *Journal of Electrical Engineering & Technology* 8.4 (2013): 694-703.
- [85] Tella, Teshome Goa, S. Simiyu Sitati, and George N. Nvakoe. "Voltage stability assessment on ethiopian 230 KV transmission network using modified voltage stability indices." *2018 IEEE PES/IAS PowerAfrica*. IEEE, 2018.
- [86] Chappa, Hemanthakumar, and Tripta Thakur. "A fast online voltage instability detection in power transmission system using wide-area measurements." *Iranian Journal of Science and Technology, Transactions of Electrical Engineering* 43. Suppl 1 (2019): 427-438.
- [87] Zhang, Yuchen, et al. "A hierarchical self-adaptive data-analytics method for real-time power system short-term voltage stability assessment." *IEEE Transactions on Industrial Informatics* 15.1 (2018): 74-84.
- [88] Kessel, P., and H. Glavitsch. "Estimating the voltage stability of a power system." *IEEE Transactions on power delivery* 1.3 (1986): 346-354.
- [89] Julian, D. E., et al. "Quantifying proximity to voltage collapse using the voltage instability predictor (VIP)." *2000 Power Engineering Society Summer Meeting (Cat. No. 00CH37134)*. Vol. 2. IEEE, 2000.
- [90] Haque, M. H. "Novel method of assessing voltage stability of a power system using stability boundary in P-Q plane." *Electric Power Systems Research* 64.1 (2003): 35-40.

REFERENCES

- [91] Balamourougan, V., T. S. Sidhu, and M. S. Sachdev. "Technique for online prediction of voltage collapse." *IEE Proceedings-Generation, Transmission and Distribution* 151.4 (2004): 453-460.
- [92] Verbic, Gregor, and Ferdinand Gubina. "A new concept of voltage-collapse protection based on local phasors." *IEEE Transactions on Power Delivery* 19.2 (2004): 576-581.
- [93] Smon, Ivan, Gregor Verbic, and Ferdinand Gubina. "Local voltage-stability index using Tellegen's theorem." *IEEE Transactions on Power Systems* 21.3 (2006): 1267-1275.
- [94] Wiszniewski, Andrzej. "New criteria of voltage stability margin for the purpose of load shedding." *IEEE Transactions on Power Delivery* 22.3 (2007): 1367-1371.
- [95] Haque, M. H. "Use of local information to determine the distance to voltage collapse." *2007 International Power Engineering Conference (IPEC 2007)*. IEEE, 2007.
- [96] Wang, Yang, Wenyuan Li, and Jiping Lu. "A new node voltage stability index based on local voltage phasors." *Electric Power Systems Research* 79.1 (2009): 265-271.
- [97] Gu, Wei, and Qiulan Wan. "Linearized voltage stability index for wide-area voltage monitoring and control." *International journal of electrical power & energy systems* 32.4 (2010): 333-336.
- [98] Parniani, Mostafa, and Maziar Vanouni. "A fast local index for online estimation of closeness to loadability limit." *IEEE Transactions on Power Systems* 25.1 (2009): 584-585.
- [99] Seethalekshmi, K., S. N. Singh, and S. C. Srivastava. "Adaptive scheme for minimal load shedding utilizing synchrophasor measurements to ensure frequency and voltage stability." *Electric Power Components and Systems* 38.11 (2010): 1211-1227.
- [100] Tamura, Y., K. Sakamoto, and Y. Tayama. "Current issues in the analysis of voltage instability phenomena." *EPRI-EL6183 Proceedings: Bulk Power System Voltage Phenomena-Voltage Stability and Security* (1989): 5-39.
- [101] Glavic, Mevludin, and Thierry Van Cutsem. "Wide-area detection of voltage instability from synchronized phasor measurements. Part I: Principle." *IEEE Transactions on Power Systems* 24.3 (2009): 1408-1416.
- [102] Lee, Ching-Yin, Shao-Hong Tsai, and Yuan-Kang Wu. "A new approach to the assessment of steady-state voltage stability margins using the P-Q-V curve." *International Journal of Electrical Power & Energy Systems* 32.10 (2010): 1091-1098.
- [103] Althowibi, F. A., and M. W. Mustafa. "Power system network sensitivity to voltage collapse." *2012 IEEE International Power Engineering and Optimization Conference Melaka, Malaysia*. IEEE, 2012.
- [104] Dharmapala, Kalana Dulanjith, et al. "Machine learning based real-time monitoring of long-term voltage stability using voltage stability indices." *IEEE Access* 8 (2020): 222544-222555.
- [105] Song, Fei, et al. "Smart collaborative balancing for dependable network components in cyber-physical systems." *IEEE Transactions on Industrial Informatics* 17.10 (2020): 6916-6924.
- [106] Villa-Acevedo, Walter M., et al. "Long-term voltage stability monitoring of power system areas using a kernel extreme learning machine approach." *Alexandria Engineering Journal* 61.2 (2022): 1353-1367.
- [107] Li, Shuaihu, et al. "DNN-based distributed voltage stability online monitoring method for large-scale power grids." *Frontiers in Energy Research* 9 (2021): 625914.

REFERENCES

- [108] Gong, Yanfeng, and Noel Schulz. "Synchrophasor-based real-time voltage stability index." *2006 IEEE PES Power Systems Conference and Exposition*. IEEE, 2006.
- [109] Chaudhary, Priyanka, and M. Rizwan. "Voltage regulation mitigation techniques in distribution system with high PV penetration: A review." *Renewable and Sustainable Energy Reviews* 82 (2018): 3279-3287.
- [110] Nour, Morsy, et al. "Review of positive and negative impacts of electric vehicles charging on electric power systems." *Energies* 13.18 (2020): 4675.
- [111] Mohammad, Asaad, Ramon Zamora, and Tek Tjing Lie. "Integration of electric vehicles in the distribution network: A review of PV based electric vehicle modelling." *Energies* 13.17 (2020): 4541.
- [112] Zhang, Meng, et al. "Deep learning for short-term voltage stability assessment of power systems." *IEEE Access* 9 (2021): 29711-29718.
- [113] Adetokun, Bukola Babatunde, and Christopher Maina Muriithi. "Application and control of flexible alternating current transmission system devices for voltage stability enhancement of renewable-integrated power grid: A comprehensive review." *Heliyon* 7.3 (2021).
- [114] Abdollahi, Arsalan, et al. "Optimal power flow incorporating FACTS devices and stochastic wind power generation using krill herd algorithm." *Electronics* 9.6 (2020): 1043.
- [115] Abdul Rahman, Nur Atiqah, Zulkiffli Abdul Hamid, and Nur Ashida Salim. "Optimal placement of distributed generation in distribution network: a review on hybrid techniques." *Journal of Electrical and Electronic Systems Research (JEESR)* 25.1 (2024): 80-88.
- [116] Ahmad, Fareed, et al. "Optimal location of electric vehicle charging station and its impact on distribution network: A review." *Energy Reports* 8 (2022): 2314-2333.
- [117] Hu, Shuai, et al. "Reactive power operability of distributed energy resources for voltage stability of distribution networks." *Journal of Modern Power Systems and Clean Energy* 7.4 (2019): 851-861.
- [118] Ismail, Bazilah, et al. "New line voltage stability index (BVSI) for voltage stability assessment in power system: the comparative studies." *IEEE Access* 10 (2022): 103906-103931.
- [119] Sadeghi, Seyed Eshagh, and Asghar Akbari Foroud. "A general index for voltage stability assessment of power system." *International Transactions on Electrical Energy Systems* 31.12 (2021): e13155.
- [120] Mokred, Salah, Yifei Wang, and Tiancong Chen. "Modern voltage stability index for prediction of voltage collapse and estimation of maximum load-ability for weak buses and critical lines identification." *International Journal of Electrical Power & Energy Systems* 145 (2023): 108596.
- [121] Danish, Mir Sayed Shah, et al. "A recap of voltage stability indices in the past three decades." *Energies* 12.8 (2019): 1544.
- [122] Pal, Kirti, Kanika Verma, and Rupika Gandotra. "Optimal location of FACTS devices with EVCS in power system network using PSO." *e-Prime-Advances in Electrical Engineering, Electronics and Energy* 7 (2024): 100482.
- [123] Salama, Hossam S., and István Vokony. "Voltage stability indices—A comparison and a review." *Computers & Electrical Engineering* 98 (2022): 107743.

REFERENCES

- [124] Ratra, Saurabh, Rajive Tiwari, and Khaleequr Rehman Niazi. "Voltage stability assessment in power systems using line voltage stability index." *Computers & Electrical Engineering* 70 (2018): 199-211.
- [125] Reddy, S. Surender. "Optimal power flow using hybrid differential evolution and harmony search algorithm." *International Journal of Machine Learning and Cybernetics* 10.5 (2019): 1077-1091.
- [126] El-Fergany, Attia A., and Hany M. Hasanien. "Salp swarm optimizer to solve optimal power flow comprising voltage stability analysis." *Neural Computing and Applications* 32.9 (2020): 5267-5283.
- [127] Injeti, Satish Kumar, and Vinod Kumar Thunuguntla. "Optimal integration of DGs into radial distribution network in the presence of plug-in electric vehicles to minimize daily active power losses and to improve the voltage profile of the system using bio-inspired optimization algorithms." *Protection and Control of Modern Power Systems* 5.1 (2020): 1-15.
- [128] Ettappan, M., V. Vimala, Subramanian Ramesh, and V. Thiruppathy Kesavan. "Optimal reactive power dispatch for real power loss minimization and voltage stability enhancement using Artificial Bee Colony Algorithm." *Microprocessors and Microsystems* 76 (2020): 103085.
- [129] Mardanimajd, Kambiz, Shahram Karimi, and Amjad Anvari-Moghaddam. "Voltage stability improvement in distribution networks by using soft open points." *International Journal of Electrical Power & Energy Systems* 155 (2024): 109582.
- [130] Kyomugisha, Rebeccah, Christopher Maina Muriithi, and Milton Edimu. "Multiobjective optimal power flow for static voltage stability margin improvement." *Heliyon* 7, no. 12 (2021).
- [131] Adetokun, Bukola B., Christopher M. Muriithi, and Joseph O. Ojo. "Voltage stability assessment and enhancement of power grid with increasing wind energy penetration." *International Journal of Electrical Power & Energy Systems* 120 (2020): 105988.
- [132] Kyomugisha, Rebeccah, Christopher Maina Muriithi, and George Nyauma Nyakoe. "Performance of Various Voltage Stability Indices in a Stochastic Multiobjective Optimal Power Flow Using Mayfly Algorithm." *Journal of Electrical and Computer Engineering* 2022 (2022).
- [133] Jin, Yuwei, Moses Amoasi Acquah, Mingyu Seo, and Sekyung Han. "Optimal Siting and Sizing of EV Charging Station using Stochastic Power Flow Analysis for Voltage Stability." *IEEE Transactions on Transportation Electrification* (2023).
- [134] Al-Wazni, HS Mohsin, and SS Abdulla Al-Kubragyi. "A hybrid algorithm for voltage stability enhancement of distribution systems." *International Journal of Electrical and Computer Engineering* 12, no. 1 (2022): 50.
- [135] Wang, Dian, Fabrice Locment, and Manuela Sechilariu. "Modelling, simulation, and management strategy of an electric vehicle charging station based on a DC microgrid." *Applied Sciences* 10, no. 6 (2020): 2053.
- [136] Zavvos, Efstathios, Enrico H. Gerding, and Markus Brede. "A comprehensive game-theoretic model for electric vehicle charging station competition." *IEEE Transactions on Intelligent Transportation Systems* 23, no. 8 (2021): 12239-12250.

REFERENCES

- [137] Barnwal, Akhilesh Kumar, Lokesh Kumar Yadav, and Mitresh Kumar Verma. "A multi-objective approach for voltage stability enhancement and loss reduction under PQV and P buses through reconfiguration and distributed generation allocation." *IEEE Access* 10 (2022): 16609-16623.
- [138] Elshahed, Mostafa, Mohamed A. Tolba, Ali M. El-Rifaie, Ahmed Ginidi, Abdullah Shaheen, and Shazly A. Mohamed. "An Artificial Rabbits' Optimization to Allocate PVSTATCOM for Ancillary Service Provision in Distribution Systems." *Mathematics* 11, no. 2 (2023): 339.
- [139] Dehghani, Mohammad, Zeinab Montazeri, Eva Trojovská, and Pavel Trojovský. "Coati Optimization Algorithm: A new bio-inspired metaheuristic algorithm for solving optimization problems." *Knowledge-Based Systems* 259 (2023): 110011.
- [140] Houssein, Essam H., Nagwan Abdel Samee, Noha F. Mahmoud, and Kashif Hussain. "Dynamic coati optimization algorithm for biomedical classification tasks." *Computers in Biology and Medicine* 164 (2023): 107237.
- [141] Trojovský, Pavel, and Mohammad Dehghani. "Pelican optimization algorithm: A novel nature-inspired algorithm for engineering applications." *Sensors* 22, no. 3 (2022): 855.
- [142] Alamir, Nehmedo, Salah Kamel, Tamer F. Megahed, Maiya Hori, and Sobhy M. Abdelkader. "Developing hybrid demand response technique for energy management in microgrid based on pelican optimization algorithm." *Electric Power Systems Research* 214 (2023): 108905.
- [143] Yammani, Chandrasekhar, Sydulu Maheswarapu, and Sailajakumari Matam. "Optimal placement of multi DGs in distribution system with considering the DG bus available limits." *Energy and Power* 2, no. 1 (2012): 18-23.
- [144] Gupta, Santosh Kumar, and Sanjeev Kumar Mallik. "Voltage Stability Assessment of Power System Using Line Indices with Wind System and Solar Photovoltaic Generation Integration." *Journal of Operation and Automation in Power Engineering* 13.4 (2025): 303-314.
- [145] Martyushev, Nikita V., Boris V. Malozyomov, Svetlana N. Sorokova, Egor A. Efremenko, and Mengxu Qi. "Mathematical Modeling the Performance of an Electric Vehicle Considering Various Driving Cycles." *Mathematics* 11, no. 11 (2023): 2586.
- [146] Rathore, Arun, Anupam Kumar, Sunil Kumar Shukla, and Narayan Prasad Patidar. "Optimal Allocation of Hybrid Renewable Energy System in Distribution Network using Arithmetic Optimization Algorithm." *Wind Engineering* (2023): 0309524X231166859.
- [147] Rekha, Rekha, and Shankaralingappa Channappa Byalihal. "Optimal allocation of solar and wind distributed generation using particle swarm optimization technique." *International Journal of Electrical and Computer Engineering* 13, no. 1 (2023): 229.
- [148] Vandrasi, Raja Kumar, Bali Sravana Kumar, and Ramesh Devarapalli. "Solar photo voltaic module parameter extraction using a novel Hybrid Chimp-Sine Cosine Algorithm." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 47.2 (2025): 2041768.
- [149] Palani, Velmurugan, et al. "Optimal sizing and smart charging abilities of electric vehicle charging station by considering quality of service using hybrid technique." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 47.2 (2025): 2032879.

REFERENCES

- [150] Keleshteri, Sobhan Farjam, et al. "New optimal planning strategy for plug-in electric vehicles charging stations in a coupled power and transportation network." *The Journal of Engineering* 2023.3 (2023): e12252.
- [151] Fathi, Mohammadreza, and Mohammad Ghiasi. "Optimal DG placement to find optimal voltage profile considering minimum DG investment cost in smart neighborhood." *Smart Cities* 2.2 (2019): 328-344.
- [152] Nara, Koichi, et al. "Implementation of genetic algorithm for distribution systems loss minimum re-configuration." *IEEE Transactions on Power systems* 7.3 (1992): 1044-1051.
- [153] Rao, Rayapudi Srinivasa, et al. "Optimal network reconfiguration of large-scale distribution system using harmony search algorithm." *IEEE Transactions on power systems* 26.3 (2010): 1080-1088.
- [154] Kumar, B. Vinod, and Aneesa Farhan. "Optimal allocation of EV charging station and capacitors considering reliability using a hybrid optimization approach." *Applied Energy* 375 (2024): 124139.
- [155] Pal, Kirti, and Tripti Kunj. "Electric vehicle fast charging station energy management system for radial distribution network with a photo-voltaic distributed generator (PV-DG)." *e-Prime-Advances in Electrical Engineering, Electronics and Energy* 9 (2024): 100694.
- [156] Kunj, Tripti, Anand Mohan, and Kirti Pal. "Two-way energy management of electric vehicle charging station." *Int. J. Power Energy Syst* 44.10 (2024): 1-8.
- [157] Kunj, Tripti, and Kirti Pal. "EVs owner benefit evaluation through energy exchange in the smart radial distribution network." *Electric Power Components and Systems* 52.9 (2024): 1513-1527.
- [158] Bilal, Mohd, et al. "AI-based approach for optimal placement of EVCS and DG with reliability analysis." *IEEE Access* 9 (2021): 154204-154224.
- [159] Huang, Guokai, and Yonglu Fu. "Stepwise reactive power control for adaptive voltage regulation in high-penetration PV systems." *Electric Power Systems Research* 256 (2026): 112928.
- [160] Memarzadeh, Gholamreza, Mohammadreza Arabzadeh, and Farshid Keynia. "A new optimal allocation of DGs in distribution networks by using coot bird optimization method." *Energy Informatics* 6.1 (2023): 30.
- [161] Long, Hongyu, et al. "Optimal Allocation of DGs in Radial Distribution Networks Based on Improved Salp Swarm Algorithm." *Engineering Letters* 31.3 (2023).
- [162] Montoya, Oscar Danilo, et al. "A Hybrid approach based on SOCP and the discrete version of the SCA for optimal placement and sizing DGs in AC distribution networks." *Electronics* 10.1 (2020): 26.
- [163] Benkhetta, Djemoui, Abdelhafid Rouina, and Abdelouahab Necira. "Optimal placement and sizing of DG units using LCA algorithm." *EAI Endorsed Transactions on Energy Web* 11 (2024).
- [164] Shawon, Shah Mohammad Rezwanul Haque, Xiaodong Liang, and Mehrnoosh Janbakhsh. "Optimal placement of distributed generation units for microgrid planning in distribution networks." *IEEE Transactions on Industry Applications* 59.3 (2023): 2785-2795.

REFERENCES

- [165] Habibi, Jaber, et al. "Comprehensive Review of the Requirements of AC Transmission Grid Codes and the Role of FACTS Devices in Integrating Renewable Power Plants." *Results in Engineering* (2026): 110080.
- [166] Painuli, Shefali, et al. "Effects on distribution system voltage stability including electric vehicles and its enhancement by placing DG at optimal location." *Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE)*. 2018.
- [167] Kanojia, Sarika S., and Bhavik N. Suthar. "Voltage stability index: a review based on analytical method, formulation and comparison in renewable dominated power system." *Int. J. Appl. Power Eng* 13.2 (2024): 508-520.
- [168] Kanojia, Sarika, and Bhavik N. Suthar. "Voltage stability analysis in modern power system considering wind energy conversion system." *2023 IEEE IAS Global Conference on Emerging Technologies (GlobConET)*. IEEE, 2023.
- [169] Bakır, Hüseyin, et al. "A novel optimal power flow model for efficient operation of hybrid power networks." *Computers and Electrical Engineering* 110 (2023): 108885.
- [170] Lyu, Shukang, et al. "Multi-Stage Voltage Control Optimization Strategy for Distribution Networks Considering Active-Reactive Co-Regulation of Electric Vehicles." *Energy Engineering: Journal of the Association of Energy Engineers* 122.1 (2025): 221.
- [171] Zhou, Zhiquan, Ashish P. Agalgaonkar, and Kashem M. Muttaqi. "Static Voltage Stability Assessment of Electricity Networks Using an Enhanced Line-Based Index." *Energies* 19.1 (2025): 177.
- [172] A. A. Kurian and O. V. Gnana Swathika O V, "Feature Evaluation of Voltage Stability Indices in Power Systems," *2025 IEEE 6th India Council International Subsections Conference (INDISCON)*, Rourkela, India, (2025), pp. 1-6
- [173] Li, Yuyan. "Advanced intelligent optimization algorithms for multi-objective optimal power flow in future power systems: A review." *arXiv preprint arXiv:2404.09203* (2024).
- [174] Zhang, Yixi, et al. "Improved hybrid algorithm-based optimization for Integrated Energy Distribution Network System: minimizing voltage deviation, line losses, and costs." *Renewable Energy Focus* 54 (2025): 100716.
- [175] Roshan, Rakesh, Padarbinda Samal, and Pampa Sinha. "Optimal placement of FACTS devices in power transmission network using power stability index and fast voltage stability index." *2020 international conference on electrical and electronics engineering (ICE3)*. IEEE, 2020.
- [176] Saini, Abhishek, and O. P. Rahi. "Optimal power flow approaches for a hybrid system using metaheuristic techniques: a comprehensive review." *International Journal of Ambient Energy* 45.1 (2024): 2345839.
- [177] Qin, Feng, et al. "Hybrid harmony search algorithm integrating differential evolution and lévy flight for engineering optimization." *IEEE Access* 13 (2025): 13534-13572.
- [178] Thanikanti, Sudhakar Babu, et al. "Optimizing radial distribution system with distributed generation and EV charging: a spotted hyena approach." *IEEE Access* 12 (2024): 113422-113441.

REFERENCES

- [179] Elnaggar, Mohamed F. "Bio-Inspired Optimization for Frequency Stability in Microgrids with Electric Vehicle Support: Towards Sustainability of Renewable Energy Systems." *International Journal of Robotics & Control Systems* 5.4 (2025).
- [180] Salama, Hossam S., and István Vokony. "Voltage stability indices–A comparison and a review." *Computers & Electrical Engineering* 98 (2022): 107743.
- [181] Valdez, Jordan, and Diego Carrión. "Hybrid Transmission Schemes for Enhancing Static Voltage Stability in Power Systems Under Variable Operating Conditions." *Energies* 19.1 (2025): 3.
- [182] Razmjooy, Navid, Mohsen Khalilpour, and Mehdi Ramezani. "A new meta-heuristic optimization algorithm inspired by FIFA world cup competitions: theory and its application in PID designing for AVR system." *Journal of Control, Automation and Electrical Systems* 27.4 (2016): 419-440.
- [183] Razmjooy, Navid, et al. "World cup optimization algorithm: Application for optimal control of pitch angle in hybrid renewable PV/wind energy system." *Metaheuristics and Optimization in Computer and Electrical Engineering*. Cham: Springer International Publishing, 2020. 25-47.
- [184] Kumar, Mahesh, et al. "Optimal multi-objective placement and sizing of distributed generation in distribution system: a comprehensive review." *Energies* 15.21 (2022): 7850.
- [185] Li, Huan, et al. "RETRACTED: Improvement of energy supply configuration for telecommunication system in remote area s based on improved chaotic world cup optimization algorithm." (2020): 116614.
- [186] Jaramillo, Manuel, Diego Carrión, and Filippas Perdikos. "Unified Loadability Quality Factor (ULQF): A bounded and interpretable voltage stability index." *International Journal of Electrical Power & Energy Systems* 172 (2025): 111175.
- [187] Baleboina, Guru Mohan, and R. Mageshvaran. "A survey on voltage stability indices for power system transmission and distribution systems." *Frontiers in Energy Research* 11 (2023): 1159410.
- [188] Eberhart, Russell, and James Kennedy. "A new optimizer using particle swarm theory." *MHS'95. Proceedings of the sixth international symposium on micro machine and human science*. Ieee, 1995.
- [189] Elsheikh, A. H., and M. Abd Elaziz. "Review on applications of particle swarm optimization in solar energy systems." *International Journal of Environmental Science and Technology* 16.2 (2019): 1159-1170.
- [190] Ahmed, Md Irfan, and Ramesh Kumar. "A systematic review on optimal placement of CHP." *Smart Science* 11.1 (2023): 171-191.
- [191] Ahmed, Md Irfan, and Ramesh Kumar. "Locational marginal price based optimal placement of DG using stochastic radial basis function." *International Journal of Ambient Energy* 44.1 (2023): 739-749.
- [192] Ahmed, Md Irfan, and Ramesh Kumar. "Nodal electricity price based optimal size and location of dgs in electrical distribution networks using ANT LION optimization algorithm." *Distributed Generation & Alternative Energy Journal* (2023): 111-140.

REFERENCES

- [193] Gopu, Pranava, Shayeera Naaz, and Khansa Aiman. "Optimal placement of distributed generation using genetic algorithm." *2021 International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies (ICAECT)*. IEEE, 2021.
- [194] Dharageshwari, K., and C. Nayanatara. "Multiobjective optimal placement of multiple distributed generations in IEEE 33 bus radial system using simulated annealing." *2015 international conference on circuits, power and computing technologies [ICCPCT-2015]*. IEEE, 2015.
- [195] Dixit, Mukul, Prasanta Kundu, and Hitesh R. Jariwala. "Optimal placement and sizing of DG in Distribution system using Artificial Bee Colony Algorithm." *2016 IEEE 6th International Conference on Power Systems (ICPS)*. IEEE, 2016.
- [196] Green, Martin, et al. "Solar cell efficiency tables (version 57)." *Progress in photovoltaics: research and applications* 29.1 (2021): 3-15.
- [197] Singh, Bhim, Kamal Al-Haddad, and Ambrish Chandra. "A review of active filters for power quality improvement." *IEEE transactions on industrial electronics* 46.5 (1999): 960-971.
- [198] Langella, Roberto, Alfredo Testa, and Et Alii. "IEEE recommended practice and requirements for harmonic control in electric power systems." *IEEE recommended practice*. IEEE, 2014.
- [199] Golestan, Saeed, Josep M. Guerrero, and Juan C. Vasquez. "Three-phase PLLs: A review of recent advances." *IEEE Transactions on Power Electronics* 32.3 (2016): 1894-1907.
- [200] Adaptive, Phase-Locked Loop Is An. "Conventional Synchronous Reference Frame Phase-Locked Loop Is An Adaptive Complex Filter." (2014).
- [201] Matas, J., et al. "SOGI-FLL error-and-hold algorithm for improving the response in face of voltage sags and swells with a small computational burden." *International Journal of Electrical Power & Energy Systems* 153 (2023): 109403.
- [202] Sahoo, Sandeep Kumar, and Bhim Singh. "Stator Synchronization and Dynamic Operations of CBF-FLL Filter Controlled Wind Driven DFIG-Battery Based Microgrid for Rural Electrification." *2021 IEEE 6th International Conference on Computing, Communication and Automation (ICCCA)*. IEEE, 2021.
- [203] Kumar, Ankit, Vivek Narayanan, and Bhim Singh. "Implementation of CTanh-LMS and CBF-FLL Techniques for Load Compensation and Grid Synchronization of Solar PV-BES Based Microgrid." *2022 Second International Conference on Power, Control and Computing Technologies (ICPC2T)*. IEEE, 2022.
- [204] Roy, Suvom, et al. "Control of DFIG-SPV-BES microgrid with CBF prefiltered SOGI-FLL based synchronization." *IEEE Transactions on Industry Applications* 60.5 (2024): 7771-7782.
- [205] Kundu, Sombir, et al. "Power management and adaptive control method for a standalone distributed generation system under fault, DC-offset, and dynamic environments." *International Journal of Ambient Energy* 46.1 (2025): 2452245.
- [206] Kundu, Sombir, et al. "Adaptive control strategy for isolated renewable energy-based generation system with intermittency." *Electrical Engineering* 107.7 (2025): 8773-8785.
- [207] Kundu, Sombir, et al. "Robust and fast control approach for islanded microgrid system and EV charging station applications." *Electrical Engineering* 107.7 (2025): 8385-8396.

REFERENCES

- [208] Kundu, Sombir, Madhusudan Singh, and Ashutosh K. Giri. "Adaptive control approach-based isolated microgrid system with alleviating power quality problems." *Electric Power Components and Systems* 52.7 (2024): 1219-1234.
- [209] Kumar, Ajay, et al. "Active power coefficient control for grid-tied photovoltaic system under voltage distortions." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 47.2 (2025): 1788674.
- [210] Gali, Vijayakumar, et al. "Grid-Interactive Novel Resilient Control of Solar PVWind-Battery Storage Microgrid Under Distorted and Unbalanced Grid Voltages." *IEEE Transactions on Consumer Electronics* (2025).
- [211] Jalan, Subham Kumar, et al. "Power quality advancement of grid-tied photovoltaic system: using optimal phase locked loop-based control strategy." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 46.1 (2024): 9077-9096.
- [212] Athukoralalage, Dinusha Rasanjalee Kariyapperuma, Vijayakumar Gali, and B. Chitti Babu. "Design and Performance Investigation of Noncoupled High-Gain DC-DC Boost Converter With Reduced Stress and Ripple for Renewable Energy Systems." *2025 IEEE PES Conference on Innovative Smart Grid Technologies-Middle East (ISGT Middle East)*. IEEE, 2025.
- [213] Golestan, Saeed, et al. "A study on three-phase FLLs." *IEEE Transactions on Power Electronics* 34.1 (2018): 213-224.
- [214] Elgamal, Fares, Mehdi RakhtalaRostami, and Sunday Atuba. "Design and Performance Assessment of a Residential Photovoltaic System in Relation to Local Weather Conditions in Egypt." *2025 IEEE International Conference on High Performance Computing and Communications (HPCC)*. IEEE, 2025.
- [215] Pradhan, Arjyadhara, and Bhagabat Panda. "A simplified design and modeling of boost converter for photovoltaic sytem." *International Journal of Electrical and Computer Engineering* 8.1 (2018): 141.
- [216] Singh, Bhim, Ambrish Chandra, and Kamal Al-Haddad. *Power quality: problems and mitigation techniques*. John Wiley & Sons, 2014.
- [217] Eram, Trishan, and Patrick L. Chapman. "Comparison of photovoltaic array maximum power point tracking techniques." *IEEE Transactions on energy conversion* 22.2 (2007): 439-449.
- [218] Mohanty, Parimita, et al. "MATLAB based modeling to study the performance of different MPPT techniques used for solar PV system under various operating conditions." *Renewable and Sustainable Energy Reviews* 38 (2014): 581-593.
- [219] Femia, Nicola, et al. "Optimization of perturb and observe maximum power point tracking method." *IEEE transactions on power electronics* 20.4 (2005): 963-973.
- [220] Kanojia, Sarika S., Bhavik N. Suthar, and Ashutosh K. Giri. "Hybrid optimization approach for optimal location of electric vehicle charging station (EVCS) in distribution network considering voltage stability." *Smart Grids and Sustainable Energy* 10.2 (2025): 36.
- [221] Yazdani, Amirnaser, and Reza Iravani. *Voltage-sourced converters in power systems: modeling, control, and applications*. John Wiley & Sons, 2010.

REFERENCES

- [222] Rodríguez, Pedro, et al. "Multiresonant frequency-locked loop for grid synchronization of power converters under distorted grid conditions." *IEEE Transactions on Industrial Electronics* 58.1 (2010): 127-138.
- [223] Vargas, René, et al. "Predictive control of a three-phase neutral-point-clamped inverter." *IEEE Transactions on Industrial Electronics* 54.5 (2007): 2697-2705.
- [224] Mohanty, Parimita, et al. "MATLAB based modeling to study the performance of different MPPT techniques used for solar PV system under various operating conditions." *Renewable and Sustainable Energy Reviews* 38 (2014): 581-593.
- [225] Femia, Nicola, et al. *Power electronics and control techniques for maximum energy harvesting in photovoltaic systems*. CRC press, 2017.
- [226] Aredes, Mauricio, Jurgen Hafner, and Klemens Heumann. "Three-phase four-wire shunt active filter control strategies." *IEEE transactions on power electronics* 12.2 (1997): 311-318.
- [227] Rahmani, Salem, Abdelhamid Hamadi, and Kamal Al-Haddad. "A Lyapunov-function-based control for a three-phase shunt hybrid active filter." *IEEE Transactions on Industrial Electronics* 59.3 (2011): 1418-1429.
- [228] Chatterjee, Soumesh, et al. "Solar Energy-Supported User-Friendly EV Charging Solution Based on IoT." *Journal of The Institution of Engineers (India): Series B* (2024): 1-6.
- [229] Kanojia, Sarika, and Bhavik N. Suthar. "Voltage stability analysis in modern power system considering wind energy conversion system." 2023 IEEE IAS Global Conference on Emerging Technologies (GlobConET). IEEE, 2023.
- [230] Parida, Abhisek, and Bidyadhar Subudhi. "Modified leaky LMS-based control strategy for reliable operation of single-stage three-phase grid-tied PV system." *IET Renewable Power Generation* 14.9 (2020): 1453-1462.
- [231] Kanojia, Sarika S., and Bhavik N. Suthar. "Voltage stability index: a review based on analytical method, formulation and comparison in renewable dominated power system." *Int J Appl* 13.2 (2024): 508-520.

Patent Detail

1. Kanojia S. S, Suthar B. N., Giri A. K., 2025 “Controller for Solar Microgrid Systems for Enhanced Voltage Regulation and Performance Evaluation”, IP, India, 468859-001.

List of Publications

A. Journal Papers Published

- (1) Kanojia, Sarika S., and Bhavik N. Suthar. "Voltage stability index: a review based on analytical method, formulation and comparison in renewable dominated power system." *International Journal of Applied power Engineering* 13.2 (2024): 508-520. DOI: 10.11591/ijape (Scopus indexed journal).
- (2) Kanojia, Sarika S., Suthar, B.N. & Giri, A.K. "Hybrid Optimization Approach for Optimal Location of Electric Vehicle Charging Station (EVCS) in Distribution Network Considering Voltage Stability". *Smart Grids and Sustainable Energy* 10, 36 (2025). <https://doi.org/10.1007/s40866-025-00264-2>. IF-1.9. (ESCI -Web of Science and Scopus indexed journal).
- (3) Kanojia, Sarika S., Bhavik N. Suthar, and Ashutosh K. Giri. "Voltage Stability Enhancement by Optimally Placing DG in radial distribution network: A comparative analysis" *Journal of The Institution of Engineers (India): Series B (IEIB)*, volume 107, pages 1341-1356 (2026). <https://doi.org/10.1007/s40031-026-01315-7>. Springer nature. (SCOPUS indexed journal)
- (4) Kanojia, Sarika S., Bhavik N. Suthar, and Ashutosh K. Giri, "DG Placement for Enhanced Voltage Stability in EVCS Integrated Network". *International Journal of Engineering Research and Applications*. ISSN: 2248-9622, Vol. 16, Issue 8, August 2026, pp 65-73 DOI:10.9790/9622-1608657365. (UGC).

B. Conference Papers/ Book Chapter Published

- (1) S. Kanojia and B. N. Suthar, "Voltage Stability Analysis in Modern Power System Considering Wind Energy Conversion System," *2023 IEEE IAS Global Conference on Emerging Technologies (GlobConET)*, London, United Kingdom, 2023, pp. 1-7, doi: 10.1109/GlobConET56651.2023.10150149. (Scopus indexed international conference)
- (2) Kanojia, S.S., Suthar, B.N., Giri, A.K., Singh, M. (2025). Charging Technologies and Infrastructure for EVs: Trends, Technologies, and Integration Strategies for System Stability. In: Giri, A.K., Singh, M. (eds) *Electric Vehicle Charging Infrastructures and its*

LIST OF PUBLICATIONS

Challenges. Studies in Infrastructure and Control. Springer, Singapore.
https://doi.org/10.1007/978-981-96-0361-9_3. (Book Chapter- Springer Nature)

C. Journal Papers Communicated

- (1) Kanojia, Sarika S., Bhavik N. Suthar, and Ashutosh K. Giri., “Robust Synchronization and Control for Dual-Stage PV Systems: Enhancing Voltage Stability and Power Quality Under Grid Variability,” submitted to International Journal of Ambient Energy-Taylor & Francis, on date 28th November, 2025. (*SCI- Web of Science, SCOPUS indexed journal.*)

Appendix-A

A. IEEE -33 bus system data

Line data					Bus data		
Branch No.	From bus	To bus	R(Ω)	X(Ω)	P _D	Q _D	Bus
1	1	2	0.0922	0.047	0	0	1
2	2	3	0.493	0.2511	100	60	2
3	3	4	0.366	0.1864	90	40	3
4	4	5	0.3811	0.1941	120	80	4
5	5	6	0.819	0.707	60	30	5
6	6	7	0.1872	0.6188	60	20	6
7	7	8	0.7114	0.2351	200	100	7
8	8	9	1.03	0.74	200	100	8
9	9	10	1.044	0.74	60	20	9
10	10	11	0.1966	0.065	60	20	10
11	11	12	0.3744	0.1238	45	30	11
12	12	13	1.468	1.155	60	35	12
13	13	14	0.5416	0.7129	60	35	13
14	14	15	0.591	0.526	120	80	14
15	15	16	0.7463	0.545	60	10	15
16	16	17	1.289	1.721	60	20	16
17	17	18	0.732	0.574	60	20	17
18	2	19	0.164	0.1565	90	40	18
19	19	20	1.5042	1.3554	90	40	19
20	20	21	0.4095	0.4784	90	40	20
21	21	22	0.7089	0.9373	90	40	21
22	3	23	0.4512	0.3083	90	40	22
23	23	24	0.898	0.7091	90	50	23
24	24	25	0.896	0.7011	420	200	24
25	6	26	0.203	0.1034	420	200	25
26	26	27	0.2842	0.1447	60	25	26
27	27	28	1.059	0.9337	60	25	27
28	28	29	0.8042	0.7006	60	20	28
29	29	30	0.5075	0.2585	120	70	29
30	30	31	0.9744	0.963	200	600	30
31	31	32	0.3105	0.3619	150	70	31
32	32	33	0.341	0.5302	210	100	32
					60	40	33

B. IEEE -69 bus system data

Line data					Load data	
Line No.	Sending End	Receiving End	R(Ω)	X(Ω)	P_D (kW)	Q_D (KVAR)
1	1	2	0.0005	0.0012	0	0
2	2	3	0.0005	0.0012	0	0
3	3	4	0.0015	0.0036	0	0
4	4	5	0.0251	0.0294	0	0
5	5	6	0.366	0.1864	2.6	2.2
6	6	7	0.3811	0.1941	40.4	30
7	7	8	0.0922	0.047	75	54
8	8	9	0.0493	0.0251	30	22
9	9	10	0.819	0.2707	28	19
10	10	11	0.1872	0.0619	145	104
11	11	12	0.7114	0.2351	145	104
12	12	13	1.03	0.34	8	5.5
13	13	14	1.044	0.345	8	5.5
14	14	15	1.058	0.3496	0	0
15	15	16	0.1966	0.065	45.5	30
16	16	17	0.3744	0.1238	60	35
17	17	18	0.0047	0.0016	60	35
18	18	19	0.3276	0.1083	0	0
19	19	20	0.2106	0.0696	1	0.6
20	20	21	0.3416	0.1129	114	81
21	21	22	0.014	0.0046	5.3	3.5
22	22	23	0.1591	0.0526	0	0
23	23	24	0.3463	0.1145	28	20
24	24	25	0.7488	0.2475	0	0
25	25	26	0.3089	0.1021	14	10
26	26	27	0.1732	0.0572	14	10
27	3	28	0.0044	0.0108	26	18.6
28	28	29	0.064	0.1565	26	18.6
29	29	30	0.3978	0.1315	0	0
30	30	31	0.0702	0.0232	0	0
31	31	32	0.351	0.116	0	0
32	32	33	0.839	0.2816	14	10
33	33	34	1.708	0.5646	19.5	14
34	34	35	1.474	0.4873	6	4
35	4	36	0.0034	0.0084	0	0
36	36	37	0.0851	0.2083	79	56.4
37	37	38	0.2898	0.7091	384.7	274.5
38	38	39	0.0822	0.2011	384.7	274.5
39	8	40	0.0928	0.0473	40.5	28.3
40	40	41	0.3319	0.1114	3.6	2.7
41	9	42	0.174	0.0886	4.35	3.5
42	42	43	0.203	0.1034	26.4	19

43	43	44	0.2842	0.1447	24	17.2
44	44	45	0.2813	0.1433	0	0
45	45	46	1.59	0.5337	0	0
46	46	47	0.7837	0.263	0	0
47	47	48	0.3042	0.1006	100	72
48	48	49	0.3861	0.1172	0	0
49	49	50	0.5075	0.2585	1244	888
50	50	51	0.0974	0.0496	32	23
51	51	52	0.145	0.0738	0	0
52	52	53	0.7105	0.3619	227	162
53	53	54	1.041	0.5302	59	42
54	11	55	0.2012	0.0611	18	13
55	55	56	0.0047	0.0014	18	13
56	12	57	0.7394	0.2444	28	20
57	57	58	0.0047	0.0016	28	20
58	3	59	0.0044	0.0108	26	18.55
59	59	60	0.064	0.1565	26	18.55
60	60	61	0.1053	0.123	0	0
61	61	62	0.0304	0.0355	24	17
62	62	63	0.0018	0.0021	24	17
63	63	64	0.7283	0.8509	1.2	1
64	64	65	0.31	0.3623	0	0
65	65	66	0.041	0.0478	6	4.3
66	66	67	0.0092	0.0116	0	0
67	67	68	0.1089	0.1373	39.22	26.3
68	68	69	0.0009	0.0012	39.22	26.3

C. Solar PV System and CBF-FLL control Parameters:

SPV module voltage, $V_{MPP} = 437.6$ V; SPV module current, $I_{MPP} = 1774.44$ A; SPV array power, $P_{MPP} = 776.5$ kW; $N_s = 8$; $N_p = 318$; DC bus voltage, $V_{dc} = 700$ V; DC bus capacitor, $C_{dc} = 0.2017$ F; interfacing inductor, $L_f = 157.98$ μ H; sampling time, $T_s = 1$ μ s; grid voltage, $V_{LL} = 415$ V (rms).

CBF-FLL control values: $k=142$; $w_g = 314$.

System and Load parameters: DC PI controller, $K_{pd} = 45$ and $K_{id} = 1.387$; nonlinear load - three-phase diode bridge with $R = 3.143\Omega$ and $L = 50$ mH

Appendix-B

Algorithm: Hybrid Coati-Pelican Optimization (COA-POA) for Optimal EVCS Placement

- 1: Initialize system data (IEEE 33-bus: bus, line, load data)
 - 2: Define candidate buses (exclude slack bus)
 - 3: Define EVCS parameters (number of stations, charging load limits)

 - 4: Define objective functions:
 - F_1 = Voltage Deviation
 - F_2 = Voltage Stability Index (VSI)

 - 5: Initialize COA-POA parameters:
 - Population size N , maximum iterations Max_iter
 - Control parameters for Coati (exploration) and Pelican (exploitation) phases

 - 6: Initialize population:
 - Each solution $X_i = [B_1, B_2, \dots, B_n]$ (EVCS locations)
 - Assign random bus numbers within limits (2-33)

 - 7: **repeat**

 - 8: For each solution X_i do
 - 9: Place EVCS at selected buses
 - 10: Perform load flow analysis (Backward/Forward Sweep)

 - 11: Calculate objective functions:
 - Compute voltage deviation
 - Compute VSI

 - 12: Compute fitness value:
 - $F_i = w(F_1) + w(1/F_2)$

 - 13: end for

 - 14: Select best solution X_{best} with minimum fitness

 - 15: --- COATI PHASE (Exploration) ---
 - 16: For each solution X_i do
 - 17: Update position using Coati strategy:
 - $X_i^{new} = X_i + r_1 (X_{best} - X_i) + r_2 (X_j - X_k)$

 - 18: Apply constraints:
 - Bus limits: $2 \leq B_i \leq 33$
 - No duplicate EVCS locations
-

```

19:      Evaluate fitness  $F_i^{new}$ 
20:      If  $F_i^{new} < F_i$  then
21:          Update  $X_i = X_i^{new}$ 

22:      end if
23:  end for

24:  --- PELICAN PHASE (Exploitation) ---
25:  For each solution  $X_i$  do
26:      Update position using Pelican strategy:
         $X_i^{new} = X_i + r (X_{best} - X_i)$ 

27:      Apply constraints:
        Bus limits:  $2 \leq B_i \leq 33$ 
        No duplicate EVCS locations

28:      Evaluate fitness  $F_i^{new}$ 
29:      If  $F_i^{new} < F_i$ , then
30:          Update  $X_i = X_i^{new}$ 
31:      end if
32:  end for

33: until iteration =  $Max\_iter$ 

34: Report optimal EVCS locations
35: Report minimum voltage deviation and maximum VSI
36: Report improved voltage profile and system performance

end

```

Algorithm: World Cup Optimization (WCO) for Optimal DG Allocation

- 1: Initialize system data (IEEE 33-bus: bus, line, load data)
 - 2: Define candidate buses (exclude slack bus)
 - 3: Define DG parameters (size limits, number of DGs)
 - 4: Initialize WCO parameters:
 Number of teams N , number of groups G , maximum iterations Max_iter
 - 5: Initialize population:
 Each team $X_i = [B_1, B_2, \dots, B_n]$ (DG locations)
 Assign random bus numbers within limits
 - 6: **repeat**
 - 7: For each team X_i do
 - 8: Place DGs at selected buses
 - 9: Perform load flow analysis (Backward/Forward Sweep)
 - 10: Calculate objective functions:
 F_1 = Line Stability Index (LSI)
 F_2 = Line Stability Factor (LSF)
 F_3 = Fast Voltage Stability Index (FVSI)
 - 11: Compute fitness value:
 $F_i = w(F_1) + w(F_2) + w(F_3)$
 - 12: end for
 - 13: Select best team X_{best} with minimum fitness
 - 14: Divide population into G groups
 - 15: For each group do
 - 16: Evaluate teams and select top performers (winners)
 - 17: end for
 - 18: Perform knockout stage:
 - 19: Pair winning teams
 - 20: Generate new teams using:
 $X_{new} = \alpha X_i + (1 - \alpha) X_j + rand$
 - 21: For each team X_i do
 - 22: Update team position:
 $X_i^{new} = X_i + rand * (X_{best} - X_i)$
 - 23: Apply constraints:
 Bus limits: $2 \leq B_i \leq 33$
 No duplicate DG placement
 - 24: Evaluate new fitness F_i^{new}
-

```
25:      If  $F_i^{new} < F_i$  then
26:          Update  $X_i = X_i^{new}$ 
27:      end if

28:  end for

29: until iteration =  $Max\_iter$ 

30: Report optimal DG locations and sizes
31: Report improved voltage profile, reduced losses, and VSI values

end
```
