COORDINATED OPERATION OF TSO AND DSO FOR EFFICIENT GRID MANAGEMENT

MEGHA GUPTA

Department of Electrical Engineering
Indian Institute of Technology Delhi
JUNE 2022

COORDINATED OPERATION OF TSO AND DSO FOR EFFICIENT GRID MANAGEMENT

by

MEGHA GUPTA

Department of Electrical Engineering

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the

Indian Institute of Technology Delhi

JUNE 2022

I dedicate this thesis to my family for all their love and support and putting me through the best education possible.

Certificate

This is to certify that the dissertation entitled '**Coordinated Operation of TSO & DSO for Efficient Grid Management**', being submitted by **Ms. Megha Gupta** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by her in the Department of Electrical Engineering at Indian Institute of Technology Delhi, New Delhi.

Ms. Megha Gupta has worked under my supervision and has fulfilled the requirements for the submission of this dissertation, which to our knowledge has reached the requisite standard. The results obtained here have not been submitted to any other university or institute for the award of any degree.

Prof. A. R. Abhyankar
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi 110016, India

Date:

Acknowledgements

I feel immense pleasure and great privilege to express my deep gratitude to all those people who, in one way or another, have supported the realization of this work.

First and foremost, I would like to express my heartfelt gratitude to my supervisor, Prof. Abhijit R. Abhyankar for his invaluable guidance, constant supervision, inspiration and endless support throughout my Ph.D. This thesis would not have been possible without his help, support and patience. His advice and precious ideas have helped me walk through various stages of my research. Despite having the most demanding work schedules, he always makes time to mentor me during the toughest phase of my professional and personal life. He has instilled confidence in me to handle every odd situation and motivated me to do more hard work at each failure. His wise guidance, encouragement and sense of fairness throughout this work has been invaluable. I am greatly indebted to him for providing me with great opportunities every time that helped in my overall personality development. Without his inputs, I could not have finished this work. Thank you.

I am grateful to the members of my research committee, Prof. Nilanjan Senroy, Prof. B.K. Panigrahi, and Dr. Ashu Verma, for their detailed review and constructive suggestions during the progress of this research work. I would also like to express my gratitude to Dr. Anuradha Annaswamy and Dr. Noel Schulz for providing me with the opportunity to visit MIT, USA and enriching my research skills. I would like to acknowledge the support provided by Department of Science and Technology, India, under the project Grant UI-ASSIST (US-India CollAborative For Smart DiStribution System WIth STorage).

I would like to thank Dr. Deep Kiran and Dr. Kush Khanna for their immense support, guidance and patience to clear my silliest doubts during the work. I would like to thank my colleagues in the Power System Simulation Lab: Dr. Shriram Vaishya, Dr. Ashok Jadhav, Dr. Deepak Reddy, Dr. Kritika Saxena, Dr. Dushyant Sharma, Dr. Subham Sahoo, Dr. MA Maniar, Snigdha Behera, Dr. Rajiv Jha, Dr. Shiv Raman, Dr. Sayari Das, Dr. Saleem Mir, Dr. Ayesha Firdaus, Dr. Rubi Rana, Shruti Ranjan and Bharath, for all the thoughtful discussions which made me think beyond the obvious and for making our lab such a friendly place to work in. I would also like to thank my friends Dr. Tabia Ahmad, Shaziya Rasheed, Dr. Tanushree Parsai, Dr. Manishika Rawat, and Jyoti who were no less than a family at IIT Delhi and supported me through thick and thin. I wish to thank all of them for offering their assistance and valuable suggestions.

I would like to oblige the efforts and guidance of my steering supervisors during B.Tech. and M.Tech. project work for motivating me to pursue my career in research. I wish to thank all the staff members in the department and institute for the kind cooperation and support they gave throughout the Ph.D.

Finally, I would like to express my sincere thanks to my parents Mr. Ashok Gupta and Mrs. Sudha Gupta, for their unconditional love, support and the struggle they have gone through in life to ensure my continuous progress. I wish to extend my heartfelt thanks to my brother Mr. Abhishek Gupta, sister-in-law Mrs. Mugdha Agarwal and niece Misha Gupta, for their cooperation and endurance during all these years. They rendered me enormous strength during the whole tenure of my Ph.D. at IIT Delhi. I could not have achieved even a bit of success in my work without the solace, assistance and encouragement of my family. I appreciate their sacrifices and I wouldn't have been able to get to this stage without them. Thank you so much for everything.

Above all, I want to thank God for the countless blessings throughout my life.

Date:

Place: New Delhi Megha Gupta

Abstract

The research work presented in this thesis discusses the importance of performing various power system operations through coordination between transmission and distribution system operators, with the fast developments in distributed energy resources (DERs). The aim is to provide some improvements and accommodate new dimensions to the power system operations and market clearing procedures. The need for carrying out several day-to-day operations in a distributed manner with a little reciprocity of information at the common bus of connection of transmission and distribution system is emphasized in this thesis.

The integrated power system consists of transmission and distribution systems that are physically coupled with each other. Generally, both the systems are studied, controlled and managed by different entities such as TSO and DSO. For the study of one system, the other is considered as an equivalent and thus misses out on modeling certain finer aspects of another system. The current independently operating transmission and distribution (T&D) management systems are incompetent to appropriately reflect the effect of distribution system operating conditions at the transmission level. Therefore, to effectively utilize the flair of an increasing share of DERs in the distribution systems, there is an evolving need for coordination between TSO and DSO.

The direct approach to deal with this problem could be to perform the coordinated operation in a centralized manner. But this may lead to (a) numerical instability issues due to the diverse topological structures, R/X ratios, voltage and power levels of each T&D system (b) huge communication and computational burden (c) privacy issues

while sharing the network data. Thus, the decomposition or distributed method with a reduced communication burden is preferred for solving such problems in this thesis.

To achieve a global and optimal solution for the entire power system, coordinated load flow (CLF) and coordinated optimal power flow (OPF) methods are proposed in this thesis. Also, the viability of the proposed OPF framework is validated by implementing it on the test system developed on real-time simulators (RTDS and OPAL-RT).

Next, the impact of various factors like voltage-dependent loads, DG's reactive power capability, location of DGs, and network losses on the transmission voltage security is extensively analyzed in this thesis. Also, to obtain the more realistic results for voltage stability margin, continuation power flow (CPF) is performed in a coordinated fashion including both T&D systems in this thesis.

Moreover, the coordination between TSO and DSOs is required to reflect the potential of resources available in distribution system at the transmission level for the socio-economic benefit of an entire power system. In this thesis, minimal data exchange-based coordinated market operations (CMO) scheme for the day-ahead energy market is proposed. Further, another market framework is proposed that provides freedom to DERs to select among the local energy market or wholesale electricity market where they prefer to offer their generation. This will allow DSO to select the more economical way of allocating the resources utilizing the TSO-DSO coordination.

Further, to ensure the power system security in the light of intermittent RE-based DG, this thesis proposes a methodology to carry out transmission contingency analysis based on CLF. For reducing the computation time, the criteria for selecting sensitive load buses are also suggested.

The proposed methodologies have been extensively tested on multiple test systems and detailed discussions on case study results have been presented. The results substantiate the significance of TSO-DSO coordination for various power system operations.

सार

इस थीसिस में प्रस्तुत शोध कार्य वितरित ऊर्जा संसाधनों (डीईआर) में तेजी से विकास के साथ, ट्रांसमिशन और वितरण प्रणाली ऑपरेटरों के बीच समन्वय के माध्यम से विभिन्न बिजली प्रणाली संचालन करने के महत्व पर चर्चा करता है। इसका उद्देश्य बिजली व्यवस्था के संचालन और बाजार समाशोधन प्रक्रियाओं में कुछ सुधार प्रदान करना और नए आयामों को समायोजित करना है। इस थीसिस में ट्रांसमिशन और डिस्ट्रीब्यूशन सिस्टम के सामान्य बस में सूचना की थोड़ी पारस्परिकता के साथ वितरित तरीके से कई दिन-प्रतिदिन के संचालन करने की आवश्यकता पर जोर दिया गया है।

एकीकृत विद्युत प्रणाली में पारेषण और वितरण प्रणालियां होती हैं जो भौतिक रूप से एक दूसरे से जुड़ी होती हैं। आम तौर पर, दोनों प्रणालियों का अध्ययन, नियंत्रण और प्रबंधन विभिन्न संस्थाओं जैसे टीएसओ और डीएसओ द्वारा किया जाता है। एक प्रणाली के अध्ययन के लिए, दूसरे को समकक्ष माना जाता है और इस प्रकार किसी अन्य प्रणाली के कुछ बेहतर पहलुओं को मॉडलिंग करने से चूक जाता है। वर्तमान स्वतंत्र रूप से संचालित संचरण और वितरण (टी एंड डी) प्रबंधन प्रणाली उचित रूप से ट्रांसमिशन स्तर पर वितरण प्रणाली के संचालन की स्थिति का प्रभाव प्रतिबिंबित करने के लिए अक्षम हैं। इसलिए, वितरण प्रणालियों में डीईआर की बढ़ती हिस्सेदारी के प्रभाव का प्रभावी ढंग से उपयोग करने के लिए, टीएसओ और डीएसओ के बीच समन्वय की एक उभरती हुई आवश्यकता है।

इस समस्या से निपटने का सीधा तरीका केंद्रीकृत तरीके से समन्वित संचालन करना हो सकता है। लेकिन इससे (ए) विभिन्न टोपोलॉजिकल संरचनाओं, आर / एक्स अनुपात, प्रत्येक टी एंड डी सिस्टम के वोल्टेज और पावर स्तर (बी) विशाल संचार और कम्प्यूटेशनल बोझ (सी) नेटवर्क डेटा साझा करते समय गोपनीयता मुद्दों के कारण संख्यात्मक अस्थिरता के मुद्दे हो सकते हैं। इस प्रकार, इस थीसिस में ऐसी समस्याओं को हल करने के लिए कम संचार बोझ के साथ अपघटन या वितरित विधि को प्राथमिकता दी जाती है।

संपूर्ण विद्युत प्रणाली के लिए एक वैश्विक और इष्टतम समाधान प्राप्त करने के लिए, इस थीसिस में समन्वित लोड प्रवाह (सीएलएफ) और समन्वित इष्टतम बिजली प्रवाह (ओपीएफ) विधियां प्रस्तावित हैं। साथ ही, प्रस्तावित ओपीएफ ढांचे की व्यवहार्यता को वास्तविक समय सिमुलेटर (आरटीडीएस और ओपल-आरटी) पर विकसित परीक्षण प्रणाली पर लागू करके मान्य किया गया है। इसके बाद, विभिन्न कारकों जैसे वोल्टेज पर निर्भर भार, डीजी की प्रतिक्रियाशील शक्ति क्षमता, डीजी का स्थान, और ट्रांसमिशन वोल्टेज सुरक्षा पर नेटवर्क हानियों के प्रभाव का इस थीसिस में व्यापक विश्लेषण किया गया है। इसके अलावा, वोल्टेज स्थिरता मार्जिन के लिए और अधिक यथार्थवादी परिणाम प्राप्त करने के लिए, इस थीसिस में टी एंड डी सिस्टम दोनों सहित एक समन्वित फैशन में निरंतरता बिजली प्रवाह (सीपीएफ) किया जाता है।

इसके अलावा, संपूर्ण विद्युत प्रणाली के सामाजिक-आर्थिक लाभ के लिए ट्रांसमिशन स्तर पर वितरण प्रणाली में उपलब्ध संसाधनों की क्षमता को प्रतिबिंबित करने के लिए टीएसओ और डीएसओ के बीच समन्वय की आवश्यकता है। इस थीसिस में, दिन-ब-दिन ऊर्जा बाजार के लिए न्यूनतम डेटा एक्सचेंज-आधारित समन्वित बाजार संचालन (सीएमओ) योजना प्रस्तावित है। इसके अलावा, एक अन्य बाजार ढांचा प्रस्तावित है जो डीईआर को स्थानीय ऊर्जा बाजार या थोक बिजली बाजार में से चुनने की स्वतंत्रता प्रदान करता है जहां वे अपनी पीढ़ी की

पेशकश करना पसंद करते हैं। यह डीएसओ को टीएसओ-डीएसओ समन्वय का उपयोग करते हुए संसाधनों के आवंटन के अधिक किफायती तरीके का चयन करने की अनुमति देगा। इसके अलावा, रुक-रुक कर आरई-आधारित डीजी के आलोक में बिजली व्यवस्था की सुरक्षा सुनिश्चित करने के लिए, यह थीसिस सीएलएफ पर आधारित ट्रांसमिशन आकस्मिकता विश्लेषण करने के लिए एक पद्धति का प्रस्ताव करती है। संगणना समय को कम करने के लिए संवेदनशील भार वाली बसों के चयन के मानदंड भी सुझाए गए हैं।

प्रस्तावित कार्यप्रणाली का कई परीक्षण प्रणालियों पर बड़े पैमाने पर परीक्षण किया गया है और केस स्टडी के परिणामों पर विस्तृत चर्चा प्रस्तुत की गई है। परिणाम विभिन्न बिजली व्यवस्था संचालन के लिए टीएसओ-डीएसओ समन्वय के महत्व को प्रमाणित करते हैं।

Contents

List of Figures

List of Tables

Nomenclature

Symbols

$\beta_{g,i}$	Offer price of i^{th} DG1
χ	Percentage of net essential demand
$\gamma_{g,i}$	Fraction of power offered by i^{th} DG1 in WEM
λ	Loading parameter
π_i	LMP of i^{th} bus
θ_i/δ_i	Voltage angle of i^{th} bus/node
D	Set of buses in distribution system
d^a	Power demand of a^{th} DS from the grid
n_p, n_q	Load exponents
r_{ij}, x_{ij}	Resistance and reactance of line connecting buses $i-j$
S_i, P_i, Q_i	Power injections at i^{th} bus
S_{ij}, P_{ij}, Q_{ij}	Power flows of line connecting buses $i-j$
T	Set of buses in transmission system
V_i	Voltage of i^{th} bus or node

$\mathcal{A}$	Set of boundary buses connecting TS and DS
$\mathcal{T}$	Set of time slots in a day
$\mathcal{C}_i(.)$	Convex cost function of generating unit at i^{th} bus
$\mathcal{DL}, \mathcal{DGL}$	Set of buses connected to Type A and Type B DS, respectively
$\mathcal{N}^a$	Set of buses in a^{th} DS
$\mathcal{N}^g$	Set of buses connected to generators in TS
$\mathcal{N}^{\mathcal{D}}$	Set of number of DSs connected at BBs
$\mathcal{N}^{cl,a}$	Set of buses with fixed loads in a^{th} DS
$\mathcal{N}^{Cl}$	Set of buses with fixed loads in TS
$\mathcal{N}^{DG1}, \mathcal{N}^{DG2}$	Set of buses connected to Type 1 and Type 2 DGs, respectively
$\mathcal{N}^{fl,a}$	Set of buses with flexible loads in a^{th} DS
$\mathcal{N}^{Fl}$	Set of buses with flexible loads in TS
$\mathcal{U}_i(.)$	Concave utility function of flexible load at i^{th} bus

Acronyms / Abbreviations

ADN	Active Distribution Network
BB	Boundary Bus
BP	Bid Price
CA	Contingency Analysis
CCPF	Coordinated Continuation Power Flow
CLF	Coordinated Load Flow

CMO	Coordinated Market Operations
CPF	Continuation Power Flow
CS	Contingency Selection
DER	Distributed Energy Resource
DG	Distributed Generation
DMS	Distribution Management System
DS	Distribution System
DSO	Distribution System Operator
EMS	Energy Management System
HGD	Heterogeneous Decomposition
KKT	Karush-Kuhn-Tucker
LEM	Local Energy Market
LM	Load Modelling
LMP	Locational Marginal Price
M-COPF	Modified Coordinated Optimal Power Flow
OPF	Optimal Power Flow
PI	Performance Index
PTDF	Power Transfer Distribution Factor
RE	Renewable Energy
RES	Renewable Energy Sources

SW	Social Welfare
T&D	Transmission and Distribution
TCPF	Transmission Continuation Power Flow
TCPF-LM	Transmission Continuation Power Flow with Load Modeling
TS	Transmission System
TSO	Transmission System Operator
VSM	Voltage Stability Margin
WEM	Wholesale Electricity Market