Active Distribution Network Operation Incorporating Distributed Generations and Compressed Air Energy Storage

by Mojtaba Jabbari Ghadi

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Li Li and Jiangfeng Zhang

University of Technology Sydney
Faculty of Engineering and Information Technology

October 2020

Faculty of Engineering and Information Technology
School of Electrical and Data Engineering

Active Distribution Network Operation Incorporating Distributed Generations and Compressed Air Energy Storage

Done by: Mojtaba Jabbari Ghadi

Email: Mojtaba.jabbarighadi@student.uts.edu.au

Supervisor: A/Prof. Li Li

E-mail: Li.Li@uts.edu.au

Co-supervisor: Dr. Jiangfeng Zhang

E-mail: Jiangfz@clemson.edu

Course code: C02018

Subject Number: Doctor of Philosophy (Ph.D.)

Dates: 10/04/2017 to 10/10/2020

University of Technology Sydney (UTS)
School of Electrical and Data Engineering,
P.O. Box 123, Broadway, Ultimo, N.S.W. 2007
Australia

Certificate of Original Authorship

I, *Mojtaba Jabbari Ghadi* declare that this thesis, is submitted in fulfilment of the requirements for the award of *PhD*, in the *SEDE/FEIT* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Signature of Student:

Mojtaba Jabbari Ghadi

Production Note:
Signature removed prior to publication.

Date: 27/07/2020

Acknowledgments

I would like to take this opportunity to thank the following people and organizations for their assistance and support during my candidature.

First, I would like to express my deep gratitude to my principal supervisor Dr. Li Li and my co-supervisor Dr. Jiangfeng Zhang for their guidance, encouragement, and belief in my abilities. Their constructive comments contributed significantly to the quality of this research.

I thank all my colleagues and friends, especially Amin Rajabi, Sahand Ghavidel, and Ali Azizivahed, with whom I have shared significant knowledge and experience during the course of my student life.

Finally, none of this would be made possible without the endless love and unconditional support of my wife and family.

Abstract

Restructuring of power systems, along with the integration of renewable energy resources in electricity networks, have transformed traditional power distribution networks (DNs) into new active distribution systems (ADSs). In addition, the rapid advancement of technology has enabled the bulk utilization of power generation units and energy storage (ES) systems in DNs. The next step in this trend is to decentralize ADSs to microgrids.

After presenting an introduction to the objectives and scope of the research in the first chapter, the second chapter aims to present a review of recent advancements in the development of ADSs. In this respect, the regulatory requirements and economic concepts, by which the traditional passive DNs have evolved into ADSs, are categorized and illustrated first. Then, the state-of-the-art of ADS formation is detailed based on the novel standpoint of grid operation factors that are involved in deregulated electricity markets at the distribution level. Additionally, this chapter presents a comprehensive review of recent advancements in the operation of ADSs. To be more specific, after some literature about the market participation of distribution system operator (DSO), distribution companies (DISCOs), and aggregated agents from economic perspectives, the impacts of energy storage systems (specifically, compressed air energy storage (CAES) and electric vehicle charging station (EVCS)) at the distribution level have been investigated. Then, technical factors suited for the secure operation of ADSs and their corresponding indices and required tools are studied.

In the third chapter, the application of CAES at the distribution level is investigated. This chapter presents the participation of an ADS equipped with a small-scale CAES (SCAES) in the day-ahead (DA) wholesale market. To make CAES applicable to DNs, the thermal-electrical setting design of the SCAES coupled with a packed-bed heat exchanger is adopted in the operation of the grid, where SCAES performs as ES for DNs to surpass existing deficiencies of battery banks. The

electrical/thermal conversion rate has been modeled for the SCAES operation. Moreover, the operation strategy of the SCAES is optimally coordinated with an electrical vehicle charging station (EVCS) as an alternative ES technology in deregulated DNs. To make EVCS simulation more realistic, the Gaussian Copula probability distribution function is used to model the behavior of the EVCS. The results obtained from different case studies confirm the value of SCAES as a reliable ES technology for DNs.

Chapter four proposes the application of SCAESs as a new potential ES technology in the daily operation of an ADS, to join the DSO for the participation in a day-ahead wholesale market. A two-agent modeling approach is formulated. The first agent is responsible for aggregating SCAES units and profit maximization of the aggregator based on the distribution local marginal price. The DSO, as the second agent, receives day-ahead scheduling from the independent SCAES aggregator and is responsible for the secure operation of the ADS utilizing solar and dispatchable distributed generations as well as purchasing power from the day-ahead wholesale market. Linear programming is used for the formulation and optimization of the SCAES aggregator, while a bi-objective optimization model (with the objectives of minimum operating cost as well as minimum power loss and emissions in different scenarios) is built for DSO scheduling.

Chapter five proposes a novel concept of mobile CAES in an electric DN to improve grid operation. The proposed configuration models transportable air storage tanks carrying stored energy among the locations motor-generators placed on some distribution nodes/buses. Employing several storage tanks, a higher dispatchability and storage capacity are obtained. To overcome routing challenges for trucks, using Google Maps Application Programming Interface, the configuration of the grid is mapped on the urban region of the city of Sydney, Australia, to accurately model distances between current and targeted locations, unavailability of tanks during traveling, route congestion, and fuel consumption. To solve the obtained CAES operation problem, a new heuristic mathematical method is proposed to

convert constraints of the mobile CAES (MCAES) model into feasible search spaces, which significantly improves the convergence quality and speed. Additionally, this method offers a technique for coding solutions to use the same solution vector for both commitment and dispatch of MCAES, which reduces the solution dimension and computational burden. Since the proposed solution method is applicable to both stationary and mobile CAESs, operating results for both cases are presented and compared. The methodology is applied to IEEE 136 bus DN in addition to IEEE 33-bus DN to demonstrate the competence of MCAES when dealing with larger-scale grids to efficiently assist the DN's operator in optimizing total operating profit, active power loss, energy not supplied (ENS), and voltage stability index of the grid. The generation of fuel-based generators is also optimized to maintain the secure operation of the grid.

Finally, the last chapter presents a summary of research done in this thesis along with future reserch plan.

Keywords:

Active distribution systems, Microgrids, Distributed energy resources, Energy storage systems, Electric vehicles, Network management, ADS planning, Distribution system operator, Distribution aggregator, Day-ahead wholesale market, Locational marginal price, Small-scale compressed air energy storage, mobile storage technology, grid operation.

Publications and Conference Contributions

The following publications are part of the thesis.

Journal publications

[1] Ghadi, M. Jabbari, et al. "A review on economic and technical operation of active distribution systems." Renewable and Sustainable Energy Reviews 104 (2019): 38-53.

[2] Ghadi, Mojtaba Jabbari, et al. "From active distribution systems to decentralized microgrids: A review on regulations and planning approaches based on operational factors." Applied Energy, 253 (2019): 113543.

[3] Ghadi, Mojtaba Jabbari, et al. "Day-Ahead Market Participation of an Active Distribution Network Equipped with Small-Scale Compressed Air Energy Storage Systems." IEEE Transactions on Smart Grid, 11, 04 (2020).

[4] Ghadi, Mojtaba Jabbari, et al. "Application of Small-Scale Compressed Air Energy Storage in the Daily Operation of an Active Distribution System." Energy (2021): 120961.

[5] Ghadi, Mojtaba Jabbari, et al. "Mobile Compressed Air Energy Storage for Active Distribution Systems." IEEE Transactions on Smart Grid [*Ready to submit*]

Table of contents

List of Tables

List of Figures

List of Abbreviations

Active distribution system planning	ADSP
Active distribution system	ADS
Advance metering infrastructure	AMI
Application Programming Interface	API
Compressed air energy storage	CAES
Copula distribution function	CDF
Day-ahead	DA
Demand response	DR
Distributed energy resource	DER
Distributed generation	DG
Distributed generation owner	DGO
Distribution company	DISCO
Distribution network	DN
Distribution system operator	DSO
Distribution locational marginal price	DLMP
Electric power system	EPS
Electric vehicle charging station	EVCS
Energy management system	EMS
Energy storage	ES
Energy not supplied	ENS
Finite step method	FDM
Geographic information system	GIS
Independent system operator	ISO
Loop power controller	LPC
Microgrid central controller	MGCC
Mobile CAES	MCAES
Momentary average interruption frequency index	MAIFI

On-load tap changer	OLTC
Packed bed heat-exchanger	PBHE
Photovoltaic	PV
Plug-in electric vehicle	PEV
Pumped-storage hydropower	PSH
Renewable energy sources	RESs
Small-scale CAES	SCAES
Soft open point	SOP
Static synchronous compensator	STATCOM
Static VAR compensator	SVC
Swarm robotics search & rescue	SRSR
System average interruption duration index	SAIDI
System average interruption frequency index	SAIFI
Transmission system operator	TSO
Transportable energy storage system	TESS
Wind turbine	WT