UNIVERSITY OF TECHNOLOGY SYDNEY

Quantifying the Resilience Enhancement of an Active Distribution System through Multi-Microgrid

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Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Li Li, Jiangfeng Zhang and Md. Jahangir Hossain

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Dillip Kumar Mishra, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy (Ph.D.) in the School of Electrical and Data Engineering, Faculty of Engineering and Information and Technology 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.

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Dedication

To my beloved parents and family.

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Nomenclature

ADS	Active distribution system
ACE	Area control error
BD	Benders-decomposition
BES	Battery energy storage
CL	Critical load
CUSUM	Cumulative-sum
DAD	Defender-attacker-defender
DOE	Department of Energy
DER	Distributed energy resource
DG	Diesel generator
DSO	Distribution system operator
ENS	Energy not supplied
EDNS	Expected demand not served
IIDG	Inverter-interfaced distributed generator
LFC	Load frequency control
LOLP	Loss of load probability
LP	Linear programming
MC	Monte Carlo
MG	Microgrid
MILP	Mixed-integer linear program
MIP	Mixed integer programming
MINP	Mixed-integer non-linear program
MPC	Model predictive control
MMC	Markov–Monte Carlo
MMG	Multi-microgrid
MSU	Mobile storage unit
NB	Naïve Bayes
OPF	Optimal power flow
PSR	Power system resilience
R&D	Research and development
RERs	Renewable energy sources
SCC	Short circuit capacity
SG	Smart grid
SOC	State of charge

TE	Transactive energy
TL	Tie-line
VSI	Voltage stability index
WRAP	Withstand- Recover- Adapt- Prevent
Chapter 3	
N_{br}	Number of branches
λ_i	Failure rate of branch *i* (*f* /km yr)
L_i	Length of a branch *i* (km)
P_j	Demand power of the j^{th} load
t_{rpr}	Fault repair time (hours)
t_{swc}	Switching time (hours)
Ω_i	Set of buses located at upstream of branch *i*
P_{DG}	Diesel generation power
P_{load}	Active power load
P_{loss}	Network power loss
P_0	Total load in the system
P_{min}	Active load in the system after the event
Chapter 4	
B	Index of energy storage units
D	Index of DG units
H	Index of MSU units
L	Index of loads
M	Index of number of loads pick up by DGs for each scenario
N	Index of disaster scenario considered
R	Index of renewable DG units
C_b	Operation cost of battery, *b*
C_d	Unit generation cost of DGs, d
C_h	Transportation cost of MSU m per kM
C_l	Load shedding cost of load, l
C_r	Unit generation cost of renewable generation unit, *r*
D_h	Distance travelled by MSU in kMs
E_b^{min}, E_b^{max}	Minimum/maximum energy stored in battery b
$E_{b,t}$	Battery SOC at time instant *t*

P_b	Active power generation by battery b
$P_{CL,k}^{j}$	Critical load of k^{th} load point restored after j^{th} extreme event
P_g	Power output of cost of the generator, g after the event
$P_{l,c}$	Load curtailment, l after the event
P_{LD}	Load demand
P_d	Active power generation by DG d
P_d^{min}/P_d^{max}	Minimum/maximum active power by DG d
P_l	Load curtailment, l after the event
$P_{LD,l}$	Total load demand at load point l
P_r	Active power generation by PV
$P_{b,t}^{ch}(P_{b,t}^{ch,max})$	Charging power (limit)
$P_{b,t}^{dis}(P_{b,t}^{dis,max})$	Discharging power (limit)
R_U , R_D	Ramp-up/down rates of DG units
$\Re_{W}$ and $\Re_{R}$	Withstand and Recover index, respectively
$\Re_{A}$ and $\Re_{P}$	Adapt and Prevent index, respectively
P_{CLi}	Critical power available after the addition of MG in kW
P_{CL0}	Critical active power available at the end of the event
$P_{CL,j}^{R}$	Critical active power available after restoration step j
$E_{th,j}^{i}$	Thevenin voltage of bus j at the t^{th} stage
$Z_{th,j}^{i}$	Thevenin impedance of bus j at the t^{th} stage
t_{ds}	Disturbance start time
$S_{L,j}^{i}$	Apparent power magnitude of bus i at the j^{th} stage
$\emptyset_j^i$	Power factor angle of bus i at the j^{th} stage
$S_{sc,min,j}^{i}$	Minimal short circuit capacity.
t_{rs}	Restoration start time
t_{rsT}	Restoration start time for traditional system
t_{reT}	Restoration end time for traditional system
Δt	Timeslot duration
$\delta_{b,t}^{i,ch}$ / $\delta_{b,t}^{i,dis}$	Charge/discharge binary indicators of BESs
t_{ds}	Disturbance start time
t_{de}	Disturbance end time
Ψ_i and $P_{lost,i}$	Total outage duration and power lost in i^{th} failure

Chapter 5	
$\mathcal{P}_W$	Wind electric power output
ρ	Air density
$\mathcal{A}_s$	Blade swept-area of wind turbine
$\mathcal{C}_p$	Power coefficient
$\mathbb{w}_s$	Wind speed
$\mathbb{w}_{rated}$& $\mathbb{w}_{cut-in}$	Rated, and cut-in wind speed
$\mathbb{w}_{cut-out}$	Cut-out wind speed
$\mathcal{P}_{PV}$	PV output
$\mathcal{P}_{rated}$	Rated wind power
η	PV array conversion efficiency
$\emptyset$	Solar insolation
$\mathcal{A}_m$	Area of measurement
θ_A	Ambient temperature
$\mathcal{P}_{EV}$	Total charging power at the station
$\mathcal{N}_{con}$	Numbers of connected EVs at the charging station
$\mathcal{P}_{EV\_inv}$	Average charging power at each charging point
$\mathcal{N}_{plug\_out}$	Number of disconnected EVs
$k\Delta t$	Averaged charging time
$\mathcal{W}_{vol}$	Energy density
σ_r, ϱ_m, & l	Tensile stress, material density, and circular path radium
ω_m , $\mathcal{K}_F$, & $\mathcal{V}$	Spinning angular speed , flywheel shape, and flywheel volume
ω_{FH}, $\mathcal{I}$, & σ_{r_Max}	Angular velocity , inertia , and maximum tensile stress
$x, u, y,$ & $\mathcal{W}$	State, control input, output and disturbance variables
$A, B, C,$ & D	State, input, output and feedthrough matrices
$\mathcal{P}_d$, $\mathcal{P}_{PV}$, & $\mathcal{P}_W$	Diesel generator, solar, and wind power
$\mathcal{P}_{EV}$ & $\mathcal{P}_{FESS}$	Electric vehicle and FESS power
$\mathcal{P}_{BESS}$, & $\mathcal{P}_L$	BESS power and load dynamics
Δu_d & Δu_{EV}	Control input to the diesel generator and EV, respectively
$\mathcal{T}_{ij}$	Synchronizing coefficient
$\mathcal{D}$	Equivalent damping constant
$\mathcal{M}$	Equivalent inertia constant
$\Delta\mathcal{P}^i_{tie}$	Tie-line power flow exchange
$\mathcal{N}$	The number of areas that are interconnected in the system

$\mathbb{O}$	Area capacity factor
β	Frequency bias parameter
Δf	Change in frequency
$\mathcal{M}_{actual}$	Actual value
$\mathcal{M}_{mea}$	Measured value
$\mathfrak{P}_C$	Cyber-attack signal
$\mathcal{X}_a$	Random cyber-attack pattern
$\mathcal{K}_a$	Scaling attack constant
$\mathcal{S}_k$	Sample value of the signal at k^{th} time
$\mathcal{D}$	Load deviation
$\mathcal{G}$ & $\mathfrak{D}$	Statistics and drift parameter
$\mathcal{H}$	Threshold value
$\mathcal{K}_p, \mathcal{K}_p,$ & $\mathcal{K}_d$	Proportional gain, integral gain, and derivative gain
K_e & K_{ce}	Scaling parameters
e_{max}	Maximum error
Chapter 6	
N	Number of MGs
$\mathcal{C}_i$	Total cost of $MG\ i$
$\mathbb{P}_{\mathcal{W},i,t}$	Energy generation from wind in i^{th} MG at time t
$\mathfrak{C}_t^P$	Pool prices
$\mathfrak{C}_{ij}^{\mathfrak{S}}$	Reference price
$\mathfrak{C}_t^{\mathcal{B}}$	Bilateral price
$\mathfrak{C}_{ij,t}^{\mathcal{B}}$	Transaction price
$\mathfrak{C}_{G,t}^{pur}$, & $\mathfrak{C}_G^{sell}$	Buying and selling price
T^{on}, T^{mid}, T^{off}	On-, mid-, and off-peak time
$\mathcal{C}_{ij,t}$	Total energy cost
a_{ij}	Power loss
$\mathcal{C}_{\mathbb{B}_{MO},t}$	Market operator benefit
$\mathbb{P}_{\mathcal{PV},i,t}$	Energy generation from PV in i^{th} MG at time t
$\mathbb{P}_{E,i,t}$	Energy trading quantity in i^{th} MG at time t
$\mathbb{P}_{B,i,t}$	Charging /discharging rates for battery storage in i^{th} MG at time t (positive is charging, negative is discharging)
$\mathbb{P}_{LD,i,t}$	Load demand in i^{th} MG at time t
$M_{ij,t}$	Energy trading quantity

$\mathcal{A}_{\mathcal{PV},i}$	Size of the PV panel in i^{th} MG
$\eta_{\mathcal{PV}}$	Efficiency of the PV panel
$\mathfrak{S}_{\mathcal{PV},t}$	Solar radiation at time t
$\mathbb{P}_{\mathcal{WR},j,max}$	Rated wind power in i^{th} MG at time t
$\mathcal{W}_{s,t}$,$\mathcal{W}_{\mathbb{R},i}$ $\mathcal{W}_{\mathbb{CI}_i}$, and $\mathcal{W}_{\mathbb{CO},i}$	Predicated, rated, cut-in, and cut-out wind speeds in i^{th} MG at time t, respectively.
$SOC_{j,t}$	Battery state-of-charge for MG j at time t
SOC_i^{min} & SOC_i^{max}	Battery minimum and maximum SOC for MG i, respectively
$\mathbb{E}_{\mathcal{B},j}^{c}$	Battery capacity for MG i
$\overline{\mathbb{P}}_{\mathcal{B},j}$	Maximum battery charging/discharging power of MG j
Δt	Time interval
$\eta_{\mathcal{B},c}$ and $\eta_{\mathcal{B},d}$	Charging and discharging efficiency, respectively
$\mathcal{P}_{i,t}^{inj}$	Active power injection/production at i^{th} node at time t
$\mathbb{S}_{i,j,t}^{inj}$	Apparent power between nodes i & j at time t
$\mathbb{S}_{i,j}^{max}$	Maximum apparent power
$\mathcal{V}_{i,t}/\emptyset_{i,t}$	Voltage/phase angle at i^{th} node at time t
$\mathcal{V}_t^{min}/\mathcal{V}_t^{max}$	Minimum/maximum voltage magnitude
$\mathbb{P}_{LD,i}$	Demand profile of MG
$\mathbb{P}_{LD,i}^{actual}$	Actual demand
$\mathbb{P}_{LD,i}^{nc}$	Non-critical load
$\mathfrak{B}$ & $1-\mathfrak{B}$	Percentage of non-critical and critical load, respectively.
$\mathfrak{R}$	Resiliency
$\mathbb{K}_{pu}$, & $\mathbb{K}_{pr}$	Public and private key
$\mathcal{U}$ and $\mathbb{X}$	Plaintext and ciphertext
f	Homomorphic function
$\mathbb{b}$	Balance
$\mathbb{R}$	Energy trading
$\mathbb{Z}_{\mathbb{i}}$	Modulus
$\mathbb{L}$ and $\mathbb{G}$	Lowest common multiple and greatest common factor, respectively

List of Publications

Published

Journals:

1. **D. K. Mishra**, et al, "A review on resilience studies in active distribution systems", *Renewable and Sustainable Energy Reviews*, Vol-135, 110201, 2021 (**IF: 16.799,** Q1)

2. **D. K. Mishra**, et al, "Resilient control based frequency regulation scheme of isolated microgrids considering cyber attack and parameter uncertainties", *Applied Energy*, Vol-306, 118054, 2022 (**IF: 11.446,** Q1).

3. **D. K. Mishra**, et al, "Active distribution system resilience quantification and enhancement through multi-microgrid and mobile energy storage", *Applied Energy*, Vol-311, 118665, 2022 (**IF: 11.446,** Q1).

4. **D. K. Mishra**, et al, "Significance of SMES Devices for Power System Frequency Regulation Scheme considering Distributed Energy Resources in a Deregulated Environment", *Energies*, Vol-15, Issue-5, pp-1766, 2022 **(IF: 3.252,** Q2**)**

Conference:

5. **D. K. Mishra**, et al. "Proposing a Framework for Resilient Active Distribution Systems using Withstand, Respond, Adapt, and Prevent Element", *2019 29th Australasian Universities Power Engineering Conference (AUPEC),* 2019.

6. **D. K. Mishra**, et al, "A Resilience Quantification Framework and Enhancement Scheme for Active Distribution Networks", *2021 IEEE PES General Meeting Poster Session*, 2021.

7. **D. K. Mishra**, et al, "A Resilient Multi-Microgrid based Transactive Energy Framework for Future Energy Markets", *2022 IEEE PES General Meeting Student Poster Session & Competition,* 2022.

Research Showcase:

8. **D. K. Mishra**, et al, "Quantification and Enhancement of Resilience through Multi-Microgrids", *Three Minutes Thesis Competition, School of Electrical and Data Engineering HDR Online Showcase Competition, University of Technology Sydney*, 2020.

9. **D. K. Mishra**, et al, "A Novel Approach to Quantify the Resilience of Active Distribution Networks", *The Next Generation Technology Project | Showcase and Awards 2021*, *Electrical Energy Society of Australia*, Australia, 2021.

10. **D. K. Mishra**, et al, "A Blockchain-enabled Transactive Energy Framework for Future Energy Markets", *IEEE NSW Chapter, UNITE* 2022

Submitted

1. **D. K. Mishra**, et al, "Resilience-Driven Scheme in Multiple Microgrids with Transactive Energy System using Blockchain Technology", *IEEE Transactions on Industrial Informatics,* 2022 (**IF: 11.648**).

2. **D. K. Mishra**, et al, "A Detailed Review on Power System Resilience Enhancement Pillars: Smartening, Hardening, Distributing, and Building", *Renewable and Sustainable Energy Reviews,* 2022 (**IF: 16.799**).

Collaboration research outcome

Published

1. **D. K. Mishra**, et al, "A review on solid-state transformer: A breakthrough technology for future smart distribution grids", *International Journal of Electrical Power and Energy Systems*, Vol-133, 107255, 2021, (**IF: 5.659**).

2. M. J. Ghadi, A. Azzizavahad, **D. K. Mishra**, L. Li, J. Zhang, "Application of small-scale compressed air energy storage in the daily operation of an active distribution system", *Energy,* Vol-231, 120961, 2021 **(IF: 8.857).**
3. S. R. Das, P. K. Ray, A. Mohanty **D. K. Mishra**, "An Advanced Wavelet Transform based Shunt Hybrid Active Filter in PV Integrated Power Distribution System for Power Quality Enhancement", *IET Energy Systems Integration*, Vol-2, Issue-4, pp 331-343, 2020.
4. S. Pati, P. Sahoo, A. K. Barisal, and **D.K. Mishra**, "Frequency Regulation of a Multi-area Renewable Power System Incorporating with Energy Storage Technologies", *Advance in Systems, Control and Automations, Part of the Lecture Notes in Electrical Engineering Book Series, Springer*, Vol-708, pp. 83-92, 2021.
5. A. K. Mishra , P. K. Ray, R. K. Mallick, S. R. Das, A. Mohanty, **D. K. Mishra**, "PSO-GWO Optimized Fractional Order PID Based Hybrid Shunt Active Power Filter for Power Quality Improvements*", IEEE Access*, Vol-8, pp. 74497- 512, 2020 **(IF: 3.367)**.
6. **D. K. Mishra**, et al, "Effect of Superconducting Magnetic Energy Storage on Two Agent Deregulated Power System Under Open Market", *Materials Today: Proceedings, Elsevier*, Vol-21, Part 4, pp. 1919-29, 2020.

Submitted:

7. J. Wang, **D. K. Mishra,** L. Li, and J. Zhang, "Demand Side Management for Industrial Users in Peer-to-Peer Energy Trading Market Based on Two-Level Multi-agent Reinforcement Learning", *IEEE Transactions on Energy Markets, Policy and Regulation*, 2022.

Abstract

Unfavorable events (e.g., natural disasters or man-made attacks) that occur on the mainland can affect the reliability/resiliency of power system networks. Such events may cause load demand–generation imbalance, total power outage, and partial power outage, thereby damaging the electrical infrastructure and incurring a high economic loss. A power outage is defined as a loss of load connectivity or absence of electrical connection between the generation or distribution stations and the consumer end. The utility grid plays a significant role in the power flow from generating station to the prosumer end. However, during a highly disruptive event, a utility grid may be unable to supply power to end-users because of component failure. To solve this problem, a power system at the local stage must manage the needs of local load demand.

The evolution of the technology that governs the utility grids are causing severe issues in disruptive events, thereby necessitating the concept of resilience. The increased frequency of disasters results in increased power system failures and recovery costs, making the system unreliable and non-resilient. Hence, the formation of microgrids (MGs) and multi-MGs (MMGs) can prevent total power outages and support the social economy and flexible energy management scheme. Besides, deploying MMGs with renewable energy sources is ideal because of affordability, decarbonization, supply security, and resiliency. On the other hand, concerning the series of outage events and long-term events, mobile services such as crews and mobile energy storage devices are crucial, which can quickly recover the critical load according to the priority, thereby reducing the impacts on the system.

Furthermore, the increasing frequency of extreme events has increased power outages worldwide, including in Australia. Thus, a resilient infrastructure must be constructed to reduce power system damages and benefit the social and economic impacts. Considering the above concerns, this thesis contributes to the modern power distribution system resiliency study with four manifolds: (a) significance of distributed energy resources on resilience, (b) resilience quantification framework in the wake of extreme events, (c) resilient control-based multi-microgrid scheme against threats, and (d) novel resilient energy market framework considering the microgrid outage conditions. Each technical chapter verifies its framework using various scenario studies, and enhancement of resilience is also illustrated. Finally, this thesis offers an approach to the resilient power distribution system considering sustainability, energy security, and energy equity.

Keywords:

Keywords: Active distribution system; Multi-microgrid; Transactive energy; Resilience; Withstand - Recover - Adapt- Respond (WRAP).

Active distribution system (ADS): ADSs are the distribution networks of power system which plays a key role to control the parameter of distributed generations (DGs) like generators (renewable or non-renewable based sources), loads, and storages (fixed and mobile). Besides, it coordinates the power flow (active and reactive) and controls the voltage and fault levels.

Multi-microgrid (MMG): It is an interconnection of a microgrid in a single platform through a tie switch. It is also called coupled microgrid, networked microgrid, and interconnected microgrid. To improve reliability and resiliency, the contribution of MMGs is significantly high.

Transactive Energy (TE):

Defined by, Gridwise council, " a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter".

The smart grid evolved as an emerging technology in the power system in which the energy trading services can take place and the prosumer plays a major role in buying and selling the power. This technology is called TE, where prosumers trade energy economically. In the TE framework, two major factors are considered, control and economic operation.

Resilience: The word resilience originates from the Latin word *resilio*, which means to "spring back." However, the dictionary meaning indicates that this term refers to the capability to recover immediately from disruptive events. Moreover, resilience could be hypothesized to refer to high-impact, low-possibility events. The main idea behind resilience theory is not merely to battle all-natural disasters but also to have immediate recovery operational measures. For low-probability and extreme events, the post-disruption stage is considered vital.

Withstand - Recover - Adapt- Respond (WRAP):

- Withstand refers to the ability or the resistance of the system against high-disruptive events.
- Recover is relevant to the rapidity of the system, which can be measured after the event hits the network.
- Adapt related to the interdependencies and resourcefulness, which are mainly focusing on the extensibility of the system during the events.
- Respond makes reference to predictability, which relates to reliable forecasting and precise decision-making to battle against extreme events.