



OPTIMUM DG ALLOCATION CONSIDERING PROTECTION COORDINATION AND NETWORK PERFORMANCE EVALUATION

By

AHMED MOHAMED ABDELBASET AHMED

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
In
Electrical Power and Machines Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2020

OPTIMUM DG ALLOCATION CONSIDERING PROTECTION COORDINATION AND NETWORK PERFORMANCE EVALUATION

By

AHMED MOHAMED ABD ELBASET AHMED

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
In
Electrical Power and Machines Engineering

Under the supervision of

Prof. Essam M.Aboul-Zahab

Professor of Electrical Power Engineering
Electrical Power and Machines Department
Faculty of Engineering
Cairo University

Prof. Mohamed A. Moustafa Hassan

Professor of Control in Power systems
Electrical Power and Machines Department
Faculty of Engineering
Cairo University

Assoc. Prof. AboulFotouh Abdel Rehiem Mohamed

Associate Professor in Electrical Power Engineering
Electrical Power and Machines Department
The Higher Institute of Engineering
El-Shorouk Academy

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2020**

Engineer: Ahmed Mohamed Abd-Elbaset Ahmed
Date of Birth : 21 / 5 / 1985
Nationality : Egyptian
E-mail : Ahmed_baset2007@yahoo.com
Phone. : 01001617009
Address : 11 sharq El-seka El hadid street Ahmed
Essmat, Ain shams, Cairo, Egypt
Registration Date : 1 / 10 / 2015
Awarding Date : / / 2020
Degree : Doctor of Philosophy
Department : Electrical Power and Machines Engineering



Supervisors : **Prof. Dr.** Essam Mohamed Aboul-Zahab
Prof. Dr. Mohamed Ahmed Moustafa Hassan
Assoc. Prof. AboulFotouh Abdel Rehiem Mohamed (The Higher
Institute of Engineering at Elshorouk City)

Examiners : **Prof. Dr.** Essam Mohamed Aboul-Zahab (Thesis main advisor)
Prof. Dr. Mohamed Ahmed Moustafa Hassan (Advisor)
Prof. Dr. Hossam Kamal Mohamed Youssef (Internal Examiner)
Prof. Dr. Almoataz Youssef Abdelaziz (External Examiner)
(Ain Shams University)

**Title of Thesis: Optimum DG Allocation Considering Protection Coordination
and Network Performance Evaluation**

Key Words:

Distributed Generation, Radial Systems, Optimum allocation, Protection Coordination.

Summary :

This thesis introduces two strategies associated with recloser fuse miscoordination (RFM) that arises due to the presence of DG in the distribution networks.

The first strategy presents an approach to determine the maximum suitable size of DG with certain constraints to avoid the coordination failure between the existing devices in addition to other keys taken into consideration such as improving voltage profile, reducing fault current and minimize system power loss.

The second approach is used to obtain the optimum settings for recloser and fuses in the presence of single/multiple DG units which can coordinate properly with different sizes and location of DGs in the system with suitable time coordination interval. Two multi objective functions are proposed. The first associated with RFM problem to minimize the sum of operating time of all fuses and recloser and the second is consider technical benefits such as voltage profile enhancement and power loss reduction.

Disclaimer

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

Name: **Ahmed Mohamed Abdelbaset**

Date:

Signature: *Ahmed Abdelbaset*

Acknowledgments

Thanks to ALLAH who gives us the power and hope to succeed.

I am honored to record my deepest sense of gratitude and thanks to **Prof. Dr. Essam Eldin M. Abu Elzahab – Cairo University, Prof. Dr .Mohamed A. Moustafa Hassan – Cairo University** and to **Assoc.Prof. Aboulfotouh Abdelrehim Mohamed – Head of Electrical Power and Machines Department – El-Shorouk Academy** for their valuable supervision, continuous encouragement, stimulating discussion, generous guidance, and scientific support, without which the present study would not have been carried out.

I wish to express my thanks to **Prof. Dr. Essam Eldin M. Abu Elzahab** and **Prof. Dr. Mohamed A. Moustafa Hassan** for their critical readings, guidance, discussion and also the useful suggestions to my thesis.

Furthermore, I would like to express my deepest gratitude and thanks to all staff members of the Electric Power and Machines Department in El-Shorouk Academy for their encouragement and support for contributing to such an inspiring and pleasant atmosphere.

There are not enough words to thank **my parents, my brothers and my sister** for the good family atmosphere, which helped in completing this thesis and encouragement during all time of hard work to complete it.

Very special thanks to **my wife** who stood by me and encouraged me.

Last but not least, special thanks to **my sons Mohamed and Moustafa** who are my absolute happiness.

Table of Contents

Disclaimer.....	i
Acknowledgments.....	ii
Table of Contents.....	iii
List of Tables.....	vi
List of Figures.....	vii
List of Abbreviations.....	ix
List of Symbols.....	x
Abstract.....	xi
Chapter 1: Introduction.....	1
1.1 Preface.....	1
1.2 Problem Statement.....	2
1.3 Thesis Objectives.....	3
1.4 Thesis Contribution	3
1.5 Organization of the Thesis	4
Chapter 2: Impact of DG on Distribution System.....	5
2.1 Overview	5
2.2 Definitions of Distributed Generation	6
2.3 Types and Technologies of Distributed Generation	7
2.4 Benefits of Distributed Generation.....	10
2.4.1 Customer Benefits of Distributed Generation.....	10
2.4.2 Supplier Benefits of Distributed Generation.....	10
2.4.3 Network Benefits of Distributed Generation	11
2.5 Disadvantages of Distributed Generation	11
2.6 Impact of Distributed Generation on Distribution Network Performance.....	11
2.6.1 Impact of DG on Voltage Regulation.....	12
2.6.2 Impact of DG on Loss Reduction.....	13
2.7 Impact of DG on Power Quality.....	14
2.7.1 Over Voltage	14
2.7.2 Under Voltage	15
2.7.3 Voltage Sag	15
2.7.4 Voltage Swell	16
2.7.5 Impact of DG on Harmonics	16
2.8 Protection Miscoordination	18
2.8.1 Modeling of Protection Devices.....	18
2.8.1.1 Modeling of Recloser.....	18
2.8.1.2 Modeling of Fuse.....	19
2.8.2 Protection Coordination Scheme.....	20
2.9 Impact of DG on the protection of distribution networks.....	21
2.9.1 False Tripping of Feeder	21
2.9.2 Blinding of Protection.....	21
2.9.3 Increase in Short Circuit Levels	22

2.9.4 Automatic Reclosing	23
2.9.5 Unintentional Islanding.....	23
2.9.6 Change in Fault Impedance.....	23
2.9.7 Reverse Power Flow.....	24
2.9.8 Fuse Saving Operation.....	24
2.10 Impact of DG on Recloser Fuse Miscoordination Problem	24
2.10.1 DG and fault located behind recloser	25
2.10.2 Fault located in front of recloser and DG located behind recloser.....	25
2.10.3 Fault located behind recloser and DG located in front of recloser.....	26
2.10.4 Fault and DG located in front of recloser	26
Chapter 3: Literature Review on Solutions for Coordination Problems.....	28
3.1 Disconnecting DG units during Fault Condition.....	28
3.2 Limiting Penetration Level of Distributed Generation	28
3.3 Using Fault Current Limiter (FCL)	29
3.4 Modifying the Conventional Protection Devices Settings	29
3.5 Limiting DG Output Current.....	31
3.6 Selecting the Best Location of DG with Minimum Coordination Lost.....	31
Chapter 4: Optimization Techniques.....	33
4.1 Introduction	33
4.2 Whale Optimization Algorithm	33
4.2.1 Mathematic model for Whale Optimization algorithm	34
4.2.1.1 Encircling Prey Equation.....	34
4.2.1.2 Bubble-net Attacking Method (exploitation phase).....	35
4.3 Ant Lion Optimization	39
4.3.1 Operators of the ALO algorithm	39
4.3.2 Random walks of ants.....	40
4.3.3 Trapping in ant lion's pits	41
4.3.4 Building trap.....	41
4.3.5 Sliding ants towards ant lion	41
4.3.6 Catching prey and re-building the pit.....	42
4.3.7 Elitism of antlion	42
4.4 Crow Search Optimization Algorithm.....	44
Chapter 5: Design of Protection Coordination with Optimizing DG Considering Network Performance.....	49
5.1 Introduction	49
5.2 Problem Formulation	49
5.2.1 Load Flow Analysis.....	50
5.2.1.1 Algorithm Formulation.....	51
5.2.1.2 Formulation of BIBC and BCBV matrices.....	54
5.2.2 Short-Circuit Analysis	56
5.2.2.1 Fault analysis using Z -Bus method.....	56
5.2.2.2 Implementation of short circuit program.....	59

5.2.3 Coordination Settings as an Optimization Problem	59
5.3 Objective Function Formulation and Constraints.....	59
5.3.1 First Strategy	59
5.3.1.1 Multi objective function.....	60
5.3.1.2 System Constraints.....	61
5.3.2 Second Strategy.....	66
5.3.2.1 Objective Function Formulation and Constraints.....	66
5.3.2.2 Optimum Fuse-Recloser Coordination in the Presence of DGs.....	67
Chapter 6: Case Studies and Simulation Results.....	71
6.1 Application and Results for first strategy	71
6.1.1 Case study1: Modified Roy Billinton Test System (RBTS) BUS2.....	71
6.1.1.1 Design of Protective Devices.....	76
6.1.2 Case study2: IEEE 33 Bus Test System	81
6.1.2.1 Protection Devices Settings.....	85
6.2 Application and Results for Second Strategy.....	89
6.2.1 Case study: IEEE 33 Node Test System.....	89
6.2.1.1 Simulation results for the test system.....	90
6.3 Comparison of Results between Proposed Methodology and Other Methodologies	104
Chapter 7: Conclusions and Future Work.....	106
7.1 Conclusions	106
7.2 Contribution of the Thesis.....	107
7.3 Future Work	107
References.....	108
Appendices.....	116
Appendix A: Data of RBTS BUS-2 distribution system.....	116
Appendix B: Line and Load data for IEEE 33-Bus test System.....	118
Appendix C: Published Paper from this Thesis.....	120

List of Tables

Table 2.1 : Categories and ratings of DG	7
Table 2.2 : Technologies for distributed generation.....	9
Table 2.3: Harmonic current injection requirements for distributed generators per IEEE519-1992.	17
Table 2.4 : Constants of inverse time current characteristic curve	19
Table 2.5 : Summary of the possible miscoordination pattern.....	27
Table 5.1 : Description for fault currents seen by fuse and recloser.....	63
Table 6.1 : Load flow solution for RBTS Bus2 test system	74
Table 6.2 : Three phase short circuit current for RBTS test system	75
Table 6.3: Settings of protection scheme.....	76
Table 6.4: Fault current after adding DG at the located bus.....	78
Table 6.5: Maximum permissible sizes of DG for all status.....	80
Table 6.6: Maximum size according to DG location with loss reduction and minimum voltage profile	81
Table 6.7: Load flow solution for IEEE-33 bus test system.....	83
Table 6.8 : Three phase short circuit current for the test system	84
Table 6.9: Settings of protection scheme.....	85
Table 6.10: DG penetration at different locations along the system.....	87
Table 6.11: Operating sequences for the protective devices for any fault in the system	90
Table 6.12 : Maximum fault current across each protective devices without DG for faults at different nodes.....	93
Table 6.13: Optimum settings of protection scheme without DG.....	94
Table 6.14: Optimum Size of single DG achieving protection coordination	96
Table 6.15: Maximum fault current across each protective devices with Single DG unit	98
Table 6.16: Optimum settings of protection scheme in the presence of single DG unit	99
Table 6.17: Optimal allocation of DGs to achieve protection coordination.....	101
Table 6.18: Maximum fault current across each protective device with multiple DG.....	102
Table 6.19: Optimum settings of protection scheme in the presence of multiple DG.....	103
Table 6.20 : Comparison between different optimization methods for optimum settings for recloser and constants of fuses	105

List of Figures

Figure 2.1: Traditional concept of electrical power system.....	5
Figure 2.2: Recent conception of the electrical power system.....	6
Figure 2.3: Distributed generation types and technologies	8
Figure 2.4: Voltage regulation on a distribution feeder without and with DG	13
Figure 2.5 : Typical over voltage waveform	14
Figure 2.6: Instantaneous voltage sag caused by a SLG fault	15
Figure 2.7 : Instantaneous voltage swell caused by a SLG fault	16
Figure 2.8: Comparison of pure sinusoidal wave and distorted wave	17
Figure 2.9: Location of protective elements in radial distribution feeder.....	18
Figure 2.10: Coordination scheme between recloser and fuse.....	20
Figure 2.11: False tripping due to fault in another feeder F1	21
Figure 2.12 : Blinding of protective device due to the presence of DG	22
Figure 2.13: Fault contributions due to DG inserted in the system.	23
Figure 2.14: Reverse power flow due to DG	24
Figure 2.15: DG and fault located behind recloser	25
Figure 2.16: Fault located in front of recloser and DG beyond recloser	25
Figure 2.17: Fault located behind recloser	26
Figure 2.18: Fault located in front of recloser	26
Figure 4.1: 2D and 3D position vectors and their possible next locations.....	35
Figure 4.2: Bubble-net search mechanism implemented in WOA.....	36
Figure 4.3:Pseudo-Code of the WOA.....	37
Figure 4.4: Flowchart of the WOA.....	38
Figure 4.5: Flowchart of the ALO	43
Figure 4.6: Pseudo-Code of the ALO Algorithm.....	44
Figure 4.7 : The effect of the crow flight length on search process.....	46
Figure 4.8: Pseudo-code of the crow search algorithm.....	46
Figure 4.9: Flowchart of the CSA	47
Figure 5.1: Simple distribution system.....	52
Figure 5.2: Flowchart of the used load flow method.....	55
Figure 5.3: Fault occur at k-th bus of a typical bus of power system.....	56
Figure 5.4: Thevenin circuits of a typical bus of power system.....	57
Figure 5.5: Status of fuse-recloser coordination.....	62
Figure 5.6: Computational procedures for maximum size and location of DG.....	65
Figure 5.7: Flow chart for computational procedure of the proposed techniques	70
Figure 6.1: Single line diagram of a modified RBTS Bus2 test system	72
Figure 6.2: Active power losses in all branches for the test system.....	73

Figure 6.3: Fault current of the test system in different fault location without DG	73
Figure 6.4: Coordination curves of protective devices on feeder1	77
Figure 6.5: Voltage profile without and with DG located @ bus 4.....	79
Figure 6.6: Active power losses without and with DG located @ bus 4	79
Figure 6.7: Single line diagram for 33-bus test system	82
Figure 6.8: Active power losses in all branches for 33 bus system.....	82
Figure 6.9: Coordination curve between fuse 5 and recloser.	86
Figure 6.10: Recloser-fuse coordination margin for a 0.743 MW DG unit at bus 18	88
Figure 6.11: Voltage profile without and with DG located @ bus 18.....	88
Figure 6.12: Fault current of the test system in different location without DG	92
Figure 6.13: Time current characteristic curve of all protective devices without DG	92
Figure 6.14: Voltage profile without and with only one DG located @ bus 7	96
Figure 6.15: Fault current of the test system in different location with single DG unit	97
Figure 6.16: Time current characteristic of all protective devices after adding one DG.....	97
Figure 6.17: Variation of voltage profile without and with multiple DG units	100
Figure 6.18: Fault current of test system in different location with three DG units.....	101
Figure 6.19: Time current characteristic of all protective devices with multiple DGs.....	103

List of Abbreviations

ALO	Ant lion Optimizer Algorithm
BIBC	Bus Injection to Branch Current
BCBV	Branch Current to Bus Voltage
CB	Circuit Breaker
CSA	Crow search Algorithm
DG	Distributed Generation
DSS	Distribution System Substation
FC-MT	Fuel Cell –Micro Turbine
FMM	Fuse Minimum Melting
FTC	Fuse Total clearing
GA	Genetic Algorithm
IPM	Interior Point Method
LDC	Line Drop Compensation
LTC	Load Tap Changing
LV	Low Voltage
MT	Micro Turbine
MV	Medium Voltage
PSO	Particle Swarm Optimization
R	Recloser
RBTs	Roy Billinton Test System
RFM	Recloser Fuse Miscoordination
SI	Standard Inverse
EI	Extremely Inverse
T & D	Transmission and Distribution
THD	Total Harmonic Distortion
WOA	Whale Optimizer Algorithm

List of Symbols

n	Number of buses
F_{loss}	System power loss
P_{lossi}	Active power loss at i-th buses
Q_{lossi}	Reactive power loss at i-th buses
P_{DGi}	Real power from DGs placed at node i
P_{Di}	Load active Power at node i
V_i	Voltage magnitude at bus i
V^{Min}	Minimum Voltage limit
V^{Max}	Maximum Voltage limit
TMS	Time multiplier setting
OLF	Over load factor
t_{rec}	Operating time of recloser
I_f	Recloser fault current
I_{pickup}	Pickup current setting of recloser
M	Ratio of I_f / I_{pickup}
A,B,P	Constants based on curve characteristics
I_{max}	Max current passing through recloser
t_{fuse}	The operating time of fuse
I_{ff}	The fault current passing through fuse
a, b	Fuse constant
n_{fuse}	Total number of fuses
$t_{recfast}$	Operating time of recloser for fast mode
$t_{recslow}$	Operating time of recloser for slow mode
MFCM	Minimum Fuse coordination margin
MRCM	Minimum Recloser coordination margin

Abstract

Connection of Distributed Generation (DG) units to the distribution systems with proper allocation and size has different affirmative effects such as increasing the reliability of the network, decreasing losses, improving voltage profile, decreasing transmission and distribution energy costs and improving the power quality.

With the widespread of using DG, the connection of DGs in the distribution system might cause difficulties in the operation of protective devices and protection coordination.

This thesis introduces the problems associated with Recloser Fuse Miscoordination (RFM) that arises due to the presence of DG in the distribution networks. Thus two strategies are proposed to avoid the miscoordination between recloser and fuse.

The proposed strategies are based on the general framework to maintain the coordination between recloser and fuse in distribution systems with optimizing DG over certain constraint considering the performance of the distribution system such as voltage profile enhancement and system power loss reduction.

The first strategy presents an approach to determine the maximum suitable size of a DG that can be connected to distribution networks with certain constraints to avoid the coordination failure between the existing devices in addition to other keys taken into consideration such as improving voltage profile, reducing fault current and minimize system power loss. So this scheme has a set of necessary equations to keep the existing protection devices unchanged according to protection coordination constraint. Such equations restrict the sizing of DG sources and permit all the existent protective elements to work normally. Evolutionary Techniques namely Whale Optimizer Algorithm (WOA), Ant lion Optimizer Algorithm (ALO), and Crow Search Optimizer Algorithm (CSA) are applied to find the optimal size and location of DG for radial distribution system considering protection coordination constraints.

The performance of the suggested methodology is examined through its application to two systems. The first one is a modified Roy Billinton Test System (RBTS) BUS2 and the second is a Standard IEEE 33 node test system.

The second strategy presents an approach based on optimum recloser fuse coordination in the presence of single/multiple DG units over a certain constraint with considering power loss reduction and voltage profile enhancement. For this purpose, two multi objective optimization problems are presented. The first is based on technical impacts to determine the optimal size and location of single and multiple DG considering system power loss reduction and enhancement of the voltage profile with certain constraints and the second is used for minimizing the operating time of all fuses and recloser with obtaining the optimum settings of fuse recloser coordination characteristics with suitable time coordination interval. The Whale Optimizer Algorithm (WOA) emulates the RFM as an optimization problem and applied to solve

the formulated problem to attain a fixed recloser and fuse characteristics which can coordinate properly with different sizes, location and operating conditions of DGs in radial distribution systems.

The effectiveness of the presented methodology is examined through its application on Standard IEEE 33 node test system.

The results indicate the robustness of the proposed algorithm compared with other techniques among all the methods considered in this work for solving the RFM problem with achieving system power loss reduction and voltage profile enhancement.

The thesis evinces the importance of selecting the correct size, suitable location of DG for avoiding the miscoordination problem between the protective devices with obtaining good performance of the distribution system.