OPTIMAL PLACEMENT AND SIZING OF DISTRIBUTED GENERATION USING WHALE OPTIMIZATION ALGORITHM

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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สุวัน อุง: การกำหนดตำแหน่งและขนาดที่เหมาะสมในการติดตั้งของระบบไฟฟ้าแบบกระจายตัวโดยใช้กลวิธีการหาค่าที่เหมาะสมแบบวาฬ (OPTIMAL PLACEMENT AND SIZING OF DISTRIBUTED GENERATION USING WHALE OPTIMIZATION ALGORITHM) อาจารย์ที่ปรึกษา : อาจารย์ ดร.อุเทน ลีตน, 109 หน้า

ในระบบไฟฟ้าโดยทั่วไปมี 3 ระบบ คือ ระบบผลิต ระบบส่งจ่าย และระบบกระจายกำลังไฟฟ้า ระบบกระจายกำลังไฟฟ้าเป็นส่วนที่สำคัญที่สุดที่ควรได้รับการพิจารณา เนื่องจากเป็นระบบที่มีส่งต่อถึงผู้ใช้ได้ง่าย และยังมีประสิทธิภาพสูง แต่ในขณะนี้มีระบบไฟฟ้าแบบกระจายตัวซึ่งเป็นเทคโนโลยีใหม่ที่พึ่งเกิดขึ้นและมีบทบาทที่สำคัญสำหรับระบบไฟฟ้าในปัจจุบัน ระบบไฟฟ้าแบบกระจายตัวเป็นที่นิยมในการใช้ลดพลังงานไฟฟ้าและปรับปรุงกำลังไฟฟ้า ประสิทธิภาพของระบบจะดีขึ้นเมื่ออยู่ในตำแหน่งและขนาดติดตั้งที่เหมาะสม อย่างไรก็ตามอาจมีผลเสียจากการกำหนดขนาดและการติดตั้งที่ไม่เหมาะสม ทำให้สิ้นเปลืองพลังงานและค่าใช้จ่าย ดังนั้นในวิทยานิพนธ์นี้จึงได้ศึกษาการวางระบบและการกำหนดขนาดที่เหมาะสมของระบบไฟฟ้าแบบกระจายตัวเพื่อป้องกันปัญหาที่จะเกิดตามมา มีงานวิจัยของนักวิจัยมากมายที่ได้ศึกษาเกี่ยวกับระบบนี้เพื่อลดกำลังสูญเสียและเพิ่มการยกระดับแรงดันให้มีประสิทธิภาพขึ้น โดยส่วนใหญ่งานวิจัยเหล่านั้นได้กล่าวใช้การคำนวณโดยใช้วิธีแบบปัญญาประดิษฐ์และการวิเคราะห์ดังได้อธิบายไว้ในปริทัศน์วรรณกรรม ในวิทยานิพนธ์ฉบับนี้การหาตำแหน่งและขนาดที่เหมาะสมของระบบไฟฟ้าแบบกระจายตัว ทำได้โดยใช้กลวิธีการหาค่าที่เหมาะสมแบบวาฬ ซึ่งเป็นเทคนิคการเพิ่มประสิทธิภาพของเมตา - ฮิวริสติกแบบใหม่และเปรียบเทียบกับวิธีแบบปัญญาประดิษฐ์อื่น ๆ ซึ่งรวมถึงอัลกอริทึมทางพันธุกรรม (G A) ผึ้งเทียม (A B C) และการเพิ่มประสิทธิภาพของอนุภาค (P S O) ในงานวิจัยนี้เน้นในเรื่องของการสูญเสียกำลังไฟที่เกิดขึ้น ด้วยการศึกษาวิธีการลดการสูญเสียกำลังไฟฟ้าที่เป็นสิ่งสำคัญที่ส่งผลต่อการทำงานของระบบไฟฟ้า นอกจากนี้ ระบบไฟฟ้าแบบกระจายได้ใช้วิธีการนิวตัน-ราฟสัน เพื่อแก้ปัญหาการไหลของกระแสไฟฟ้าร่วมด้วย ผลของการไหลของกำลังไฟฟ้าได้รับการตรวจสอบด้วยซอฟต์แวร์ดิจไซเลนท์ เพื่อให้เกิดความน่าเชื่อถือและประสิทธิภาพ วิธีการที่นำเสนอนี้ได้รับการประเมินผ่านทั้ง 4 ระบบการกระจายตัวในแนวรัศมี ได้แก่ 15 บัส 33 บัส 69 บัส และ 85 บัส ผลลัพธ์ที่ได้แสดงให้เห็นว่ากลวิธีการหาค่าที่เหมาะสมแบบวาฬ ให้การแก้ปัญหาที่ดีขึ้นในแง่ของการลดการสูญเสียเมื่อเทียบกับอีก 3 วิธี ซึ่งกลวิธีการหาค่าที่เหมาะสมแบบวาฬ ได้ช่วยประหยัดค่าใช้จ่ายและใช้เวลาในการแก้ปัญหาได้น้อยลงอีกด้วย นอกจากนี้ยังเปรียบเทียบกับวิธีอื่นอีก 2 วิธี เพื่อใช้ตรวจสอบผลที่นำเสนอที่ดีกว่า ในระบบ 15 บัส ระบบเกิดการสูญเสียพลังงานลดลงถึง 37.5% ที่ระบบไฟฟ้าแบบกระจายตัวขนาด 929.5 kW ในขณะเดียวกันการสูญเสียพลังงานลดลงจาก 206.5 kW ไปเป็น 103.6 kW โดยมีตัวเก็บประจุขนาด

2.62 MW ของระบบไฟฟ้าแบบกระจายตัว ที่บัสหมายเลข 6 และพลังงานสูญเสียลดลงถึง 49.83% ในระบบ 33 บัส สำหรับระบบ 69 บัส กำลังสูญเสียลดลงจาก 245.88 kW เป็น 86 kW ซึ่งหมายถึงลดลง 64.86% ของกำลังสูญเสียที่มีอยู่ หลังจากที่ได้ติดตั้งระบบไฟฟ้าแบบกระจายตัวที่มีตัวเก็บประจุขนาด 1.887 ที่บัสหมายเลข 60 สำหรับระบบสุดท้าย กำลังสูญเสียลดลงจาก 297.04 kW เป็น 149.6 kW ซึ่งหมายถึงลดลง 49.63% ของกำลังสูญเสียที่มีอยู่ หลังจากที่ได้ติดตั้งระบบไฟฟ้าแบบกระจายตัวที่บัส 8 ที่มีตัวเก็บประจุขนาด 2.434 MW จากผลการจำลองที่ได้ แสดงให้เห็นถึงประสิทธิภาพของระบบไฟฟ้าแบบกระจายตัว ในการลดการกำลังสูญเสียและปรับปรุงแรงดันไฟฟ้า การสูญเสียกำลังสามารถประหยัดมากกว่า 50% และแรงดันไฟฟ้าในบัสแต่ละตัวได้รับการปรับปรุงอย่างถูกต้อง ซึ่งระบบไฟฟ้าแบบกระจายตัวต้องมีตำแหน่งติดตั้งและขนาดที่เหมาะสม สรุปได้ว่าบทบาทของระบบไฟฟ้าแบบกระจายตัว มีความสำคัญอย่างยิ่งในการลดการสูญเสียกำลังไฟฟ้าและการปรับปรุงแรงดันไฟฟ้า รวมไปถึงตำแหน่งที่ติดตั้งของตัวเก็บประจุที่เพิ่มเข้าไปในระบบอย่างเหมาะสม เพื่อเพิ่มสมรรถนะของระบบไฟฟ้าแบบกระจายตัวอีกด้วย

สาขาวิชา วิศวกรรมไฟฟ้า
ปีการศึกษา 2560

ลายมือชื่อนักศึกษา Savan
ลายมือชื่ออาจารย์ที่ปรึกษา

SOVANN ANG : OPTIMAL PLACEMENT AND SIZING OF DISTRIBUTED GENERATION USING WHALE OPTIMIZATION ALGORITHM. THESIS ADVISOR : UTHEN LEETON, Ph.D., 109 PP.

DISTRIBUTED GENERATION/RADIAL DISTRIBUTION NETWORK/WHALE OPTIMIZATION ALGORITHM

Distributed generation (DG) is an emerging technology in electrical sector, and it is playing very important roles in electrical power system nowadays. DG is becoming more popular in power reducing and voltage profile improvement. Such benefits can be achieved and enhanced when DG is optimally located and sized in the system. However, it causes negative impacts to the system including high power loss, voltage fluctuation, and high investment cost if DG is non-optimally placed and sized in the system. Most of existing works use techniques such as computation, artificial intelligence and an analytical approach as described in the literature review. In this thesis, the optimal placement and size of DG is achieved using whale optimization algorithm (WOA) which is a novel meta-heuristic optimization techniques, and it is compared with other artificial intelligent technique including genetic algorithm (GA), artificial bee colony (ABC), and particle swarm optimization (PSO) for comparative purpose. This work emphasizes on real power loss only in the objective function by ignoring the reactive power losses which are the key to the operation of the power systems. Moreover, DG which operates injects only real power is considered while Newton-Raphson method is applied to solve power flow problem. The result of power flow of the method is verified with Digsilent software for conveying the reliability and

performance. The proposed method is evaluated through four radial distribution network including 15, 33, 69, and 85 buses. The obtained results show that WOA provides better solutions in term of loss reduction and convergence of iterations when compared with other three techniques. It provides high loss saving and spends less time to reach the solutions. Furthermore, it is compared with other two methods, and the proposed method give the better results than those of compared methods. In 15 bus system. System loss was reduced to 37.5% with DG size of 929.5kW. Meanwhile, the power loss was reduced from 206.5kW to 103.6kW with capacity of 2.62MW of DG at bus 6, and the power loss was reduced to 49.83% in 33 bus system. For 69 bus system, the power loss was decrease from 245.88kW to 86kW corresponding to 64.86% of power loss reduction after installing DG with capacity of 1.887MW at bus 60. For the last tested system, the system loss was reduced from 297.04kW to 149.6kW corresponding to 49.63% of loss mitigation after placing DG at bus 8 with capacity of 2.434MW. From the results, it is illustrated the efficiency of DG in loss reduction and voltage profile improvement. The system loss can be saved up to more than 50%, and voltage in each bus is improved significantly after installing DG to the system with optimal location and size. It can be concluded that DG roles as important key in electrical power distribution system in loss reduction and voltage profile improvement, and the optimal placement and capacity of DG can be achieved by applying the proposed method.

School of Electrical Engineering　　Student's Signature Sorann

Academic Year 2017　　Advisor's Signature

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CHAPTER I

INTRODUCTION

1.1 Background

Actually, electrical energy plays a very important role in daily human's life as well as in society. Generally, it has been considered as an essential thing for economic growth, social development, and human prosperity. Most of the equipment using in our daily life need electrical energy for the operation and use. Moreover, new and more electric devices and applications have been inventing and developing for human's use. The emerging of industrial evolution and social development cause to increase the demand for electrical power. Meanwhile, the electrical power should be reliable, accessible, affordable, qualified, and clean.

In an electrical power system, there are three divisions which are a generation, transmission, and distribution. Distribution section has been considered as the most important part among the three divisions since it is connected closely to the customers. It is the part which the voltage is stepped down from medium voltage to low voltage for consumer's utilization. Hence, the reliability of the system is mainly ensured by an efficient distribution system. With increasing of demand and network expansion, it has been cause the challenging for the engineers to maintain the quality and reliability in the system economically and effectively (Pandy and Bhadoriya, 2014). When the heavy load is connected to the system, the voltage magnitude is dropped and the system loss is also increased. In this 21st century, the electrical power supply should be able to meet customer's requirement. Based on the research, distribution has been contributed approximately 70% of the loss including primary and secondary part because the X/R ratio in distribution part is lower when compared to transmission part. As a result, it causes to increase system loss and drop voltage magnitude along radial distribution lines (Ackermann, Andersson and Sder, 2001). It is well known that distribution system has high loss compared to that of transmission system and some non -negligible loss cause the impact on financial issues and overall reliability of the system. These have forced the utilities to take action in order to reduce power loss in the system. Many methods have been proposed and considered for loss reduction such as system reconfiguration, shunt capacitor installation, on-site power generation etc.

Distributed generation (DG) is a modernized technology of power generation in this modern century in smart distribution system technology; moreover, DG is given the definition as on-site small scale power generations which are interconnected or connected directly to the distribution network (Celli and Pilo, 2001). It can be grid connected or stand alone electrical generation units which locate near the utilization site. In addition, Dulau, Abrudean and Bica (2015) have defined DG as the electrical power production near to consumer location integrating with renewable and non-renewable energy sources as illustrated in Figure 1.1. Mostly it is not required the transmission lines in order to connect DGs to the delivery system (Chiradeja, 2005; Wang and Xu, 2011). The integration of DG in distribution network can reduce the system loss and improve voltage profile effectively and economically. The trends of renewable energy consumption in the smart grid distribution have been increasing due to the environmental concern and fossil energy depletion. DG is becoming the important part of the electrical power grid development in the future since the presence of DG in distribution can improve the reliability, reduce power loss, enhance power quality, reduce transmission investment cost, and reduce greenhouse gases emission. In regarding of DG application, there are several important factors to consider such as, the DG technology, the number and capacity of DG, the type of DG connection, etc.

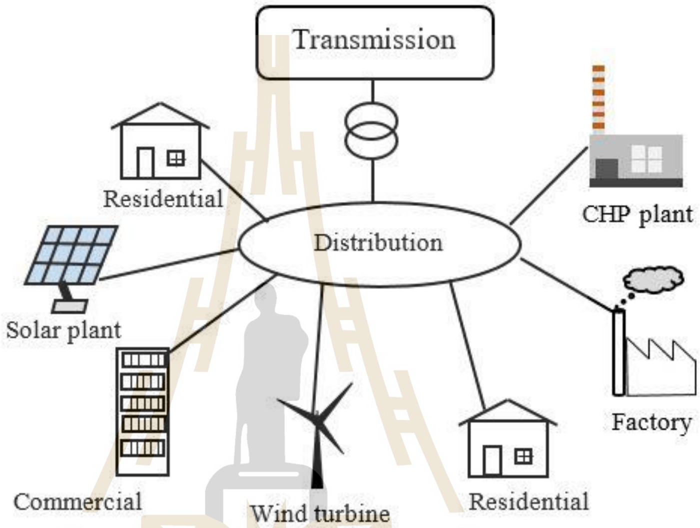

Figure 1.1 DG integration in the distribution network.

DG types can be characterized as the following:

- Type I: Inject only real power and it operates at unity power factor. (PV cells, micro turbine, fuel cells, etc.)
- Type II: Inject only reactive power. (Synchronous compensator, capacitors, Kvar compensators, etc.)
- Type III: Inject both real and reactive power. (Synchronous machines, cogeneration, gas turbine, etc.)
- Type IV: Consume reactive power but inject real power. (Induction generator in wind farms)

Investigating this optimization problem is the major motivation of the present thesis research. Optimization is the mathematical tools used to the optimal solution of the objective function, and it can be maximizing or minimizing within the required condition. Moreover, the overall objective function of the system optimization is to minimize the function without violating the system constraints. Since the optimal power flow has been proposed by French scholar in 1962s, it has taken over decades to develop the more efficient algorithm to solve optimization problems which can be linear or non-linear. Many methods have been applied to solve optimization problems up to now. It is grouped as conventional and intelligent methods. The well-known conventional methods are Newton method, Gradient method, linear programming, quadratic programming, and Interior point method have been widely used. These methods are preferred for fast calculation and online computation. On the other hand, these methods are not suitable for some optimization problems with discrete variables due to their difficulties to reach the convergence and global solution. Due to continuously developed technology in last decade, many novel intelligent techniques have been developed for dealing with complex OPF problems. Those recently intelligent methods include genetic algorithm, particle swarm Optimization, artificial bee colony, whale optimization algorithm (WOA) (Mirjalili and Lewis, 2016). Heuristic search algorithm likes GA was considered as the most suitable for solving simultaneous multi-dimensional problems for global optimum solution. Furthermore, GA can reach convergence easily and it has complex encoding and decoding operation. PSO is a heuristic method which bases on the behaviour of swarms of fish, bird, etc. has better convergence than GA due to its combination of social psychology principle and better calculation to enhance the behaviour of the swarms. ABC which was proposed by

Karaboga in 2005 was recognized as the most efficient and novel swarm intelligent technique. It is based on the intelligent behaviour of the honey bee to find the nectar sources. Also, ABC was successfully applied to solve all kinds of optimization problems so it has better performance to numerical optimization than GA and PSO. The most recent meta-heuristic WOA was proposed in 2016 by Seyedai is the algorithm based on the behaviour of foraging of a humpback whale.

DG application is a basically complex optimization problem which requires the multi-objective optimization techniques such as minimization of real and reactive power loss, node voltage deviation, carbon emission, line loading, and short circuit capacity and maximization of network reliability etc. The aim of the thesis is to determine the location and size of DG in the radial distribution system (RDN). Real power loss and voltage of the bus at which DG is placed are the setting parameters. The location of DG can be determined either by using voltage index or artificial intelligent (AI) search method. Furthermore, the size of DG can be obtained by AI search technique.

1.2 Statement of the Problem

In fact, the integration of DG in distribution network has numerous impacts on the system due to technical and safety issues (Pecas Lopes et al, 2007). In regarding of these issues, DG should be connected properly in such manner to avoid degradation of system reliability and quality. Moreover, the size and number of DG accessed also are the great importance to consider. Also, non-appropriate location and size of DG can cause to increase system losses, voltage fluctuation, voltage flicker, protection failure, harmonic, system instability, and ineffective investment cost (Mishra and Bhandakkar, 2014). Moreover, installing DG units is not straightforward, so the location and sizing of DG units should be carefully addressed.

1.3 Objective of the Study

The main purpose of this thesis is to solve the optimization of DG in term location and size in the radial distribution networks for system loss reduction and voltage improvement as well as power quality. The single objective function of overall real power loss is considered as the objective function to be minimized. Meanwhile, this research work also composes the following objectives:

1.3.1 To study the essential presence of DG in distribution network as well as the characteristic of DG technologies. Also, the benefit and drawback of DG are investigated. The distribution network in the type of radial is also explored in this work.

1.3.2 To find the optimal placement and size of DG in radial distribution network using AI search algorithms. Furthermore, the obtained results are compared with those of other two author's works for comparative aims.

1.3.3 To compare the effectiveness and performance of the AI search algorithm in solving the problem of optimal placement and size of DG. Moreover, to show the important contribution of DG in system loss deduction and voltage profile improvement in the distribution system.

1.4 Scope and Limitation of Study

In this thesis, location and size of single DG to be optimized are the main aims, and the kind of radial distribution network which consists a step down transformer supplying the power to the network is considered as the tested cases to evaluate the performance of the proposed algorithm. Moreover, the single DG which injects only real power to the system and operates at unity power factor is investigated. The kind of the DG can be PV cell, micro turbine etc. Newton-Raphson power flow computation is applied compute power loss as well as other parameters. Furthermore, Whale optimization algorithm which is a recent meta-heuristic optimization algorithm is applied to solve the problem in finding both the optimal location and size of DG in RDN. The RDN of 15, 33, 69, and 85 buses are considered as the tested cases with the algorithm. To verify the accuracy and efficiency of the proposed method, the simulation result of the proposed method is compared with that of Digsilent which is the software utilized for power flow simulation.

1.5 Benefits of Research

The importance of DG contribution in distribution network in system loss reduction, voltage profile improvement, power quality enhancement is conveyed. The optimal location and size of DG can be identified by AI search effectively, and it is a useful tool for the utilities for practical implementation of DG. Based on the obtained results, it provides the optimal solution with high reliability, and obviously, it is shown importance relationship between theoretical knowledge and real practices of DG application. Moreover, it opens the ways for other academics to study for further research about DG in the aims of enhancement of quality, reliability, economy, and clean of electrical power.

1.6 Thesis Outline

This thesis is organized into five chapters, and the brief description of each chapter is mentioned as the following:

Chapter I provides a brief introduction to the study including backgrounds, statement of the problem, objectives of the study, scope, and limitation of the study, benefits of research, and the thesis outline.

Chapter II presents an introduction of electrical power system structure is presented with the special attention to the distribution network. Thereafter, the detail of radial distribution network's configuration and issues are described. Following, the concepts and the trends of DG connecting to the network are also presented. The more details of DG involving the categories, technologies used are given. Additionally, the benefits and impacts of DG's application are mentioned, including the discussion on different issues that have occurred from DG connection in an existing distribution network.

Chapter III details various optimization methods which were applied earlier for optimal placement and size of DG are presented. Furthermore, a very recent meta-heuristic used for DG application is also mentioned, and the voltage index which is used for DG allocation is also described in this chapter. The formulation of the objective function including the mathematical formulation of loss calculation is expressed. Also, the power flow equations and system constraints involving the DG contribution are presented. Finally, a brief describe the proposed algorithm in step-by-step is provided.

Chapter IV discusses the obtained result that the proposed method has been developed and applied on four well-know RDNs as the tested cases, and the simulation result is evaluated with Digsilent which is the one of the most reliable power flow software. Finally, a decision making has been considered for the optimum location and size for DG in the tested system. Furthermore, the useful inferences have been proposed which can assist in the future in the implementation and development of distribution system with DG which provides the more efficient and productive power system.

Finally, **chapter V** summarizes the conclusions that have been extracted and highlights the contribution of this work. Also, the discussion of future work of DG is provided.

1.7 Chapter summary

This chapter has presented the general concept of electrical power system focusing on distribution system followed by the background of the distribution network and the current trend of electrical sector. Moreover, the various types of DG is presented including important roles in power system in loss reduction and voltage profile enhancement. Both traditional and artificial intelligent methods which have been applied in DG application are discussed as in literature review section.

CHAPTER II

LITERATURE SURVEY AND GENERAL REVIEW

2.1 Introduction

This chapter provides a brief overview of electrical power system's configuration with a special on radial distribution type. Moreover, the concept of DG is provided including the categories, technologies, and application that have been reported worldwide. Benefits and drawback related to DG are also presented. Meanwhile, the impacts and issues occurred due to DG installation in the distribution network are mentioned. Such problems as power loss and voltage drop because of DG are described.

2.2 Electrical Power System Overview

Generally, the conventional electrical power system is divided into three divisions: generation, transmission, and distribution which are distinguished by the voltage level adjusted by the power transformer as illustrated in Figure 2.1.

Generation is the place from which the electrical power is generated, and the typical size is higher than 500MW with the preferably generated voltage around 20kV. The generated voltage level is varied due to insulation requirements and practical design limitation. El-Hawary, (2008) stated that a large amount of electricity generation is shared by a small number of large fuel fired power plants where the high temperature is applied to produce a very high pressure of steam used to rotate the turbine for rotating the generator's shaft. Some power plants are non -pollution such as, nuclear power, wind turbine, solar photovoltaic which are mostly far away from the populated area. The electrical power generation comes from two sources. They are renewable and non-renewable energy sources. The renewable energy sources consist of solar, wind, biomass, geothermal, hydro, etc., and the non- renewable energy sources are coal, oil, natural gas. The renewable energy is considered and preferred because it is more environmentally friendly that the traditional sources. Furthermore, the generation plants are connected to the transmission network via the generation station where the voltage is stepped up to transmission level normally between 115kV to 1100kV in order to transfer with a long distance.

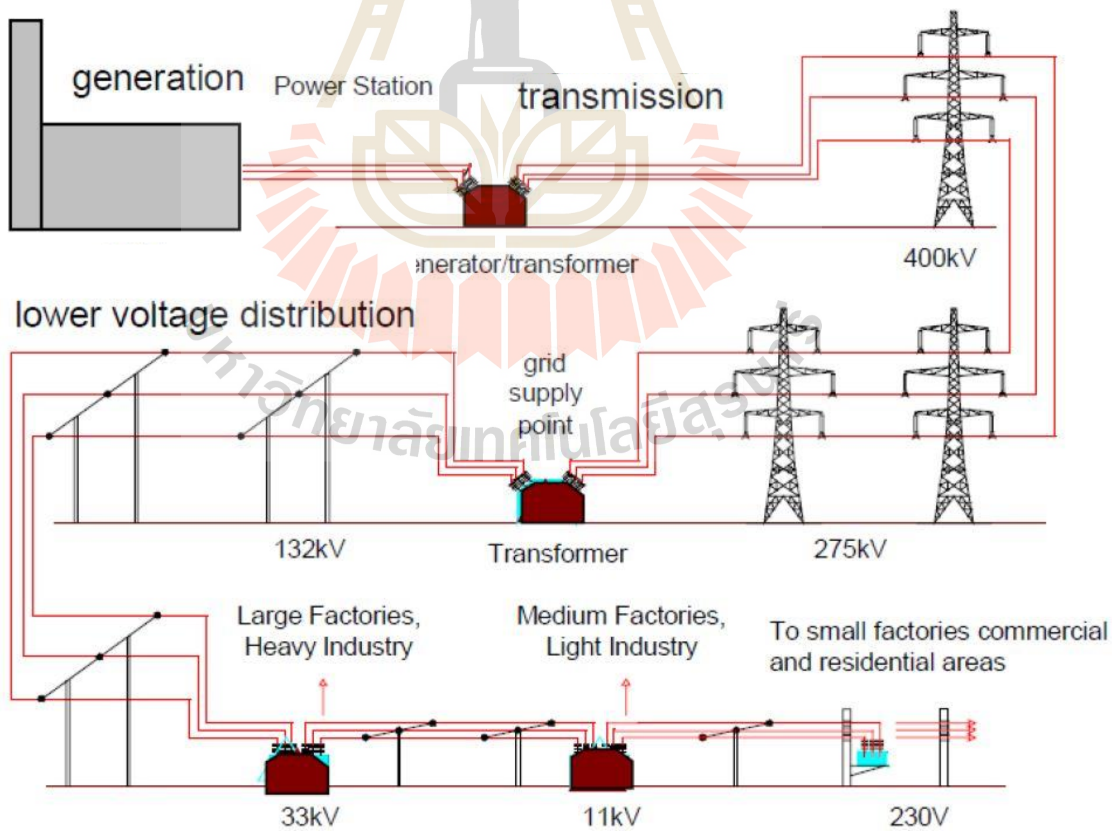

Figure 2.1 Electrical power network (IEEE Std 1410-2010, 2011).

Transmission transfers the electrical power from generation plant to the sub-station where the voltage is stepped-down for distribution level which is supplied to the load (Han, Seo, and Kim, 2012). Mostly the electrical power is transferred through an overhead network, while the percentage of underground and submarine transmission cables are relatively low. Also, the transmission network is connected to other transmission networks for exchanging the power in the reasons both of financial benefits and reliability enhancement. Normally, the electrical power is transferred with high voltage level in order to transmit for long distance with fewer power losses as well as cost-effective construction. According to the international standard, the transmission voltage is operated at 132kV or higher. Additionally, the transmission voltage at 230kV is normally considered as high voltage (HV), while the voltage above 230kV is referred as extra-high voltage (EHV). Finally, the voltage level above 1000kV is assumed as ultra-high voltage (UHV).

Distribution is considered as the final stage of power delivering to the load. The voltage of transmission level is stepped down to the distribution level which mostly ranges from 4kV to 34.5kV. Hereafter, the electricity is transferred to the distribution transformer through each feeder. Moreover, some industrial customers are supported directly from the primary feeders. The distribution network can be either overhead or underground conductor, or the underground system is preferred in the developed country due to the technical benefit and less impact on the society. As the result, the underground distribution has been arising up to 70% of the new residential construction in North America and Europe (Han, Seo, and Kim, 2012).

2.3 Distribution System

As the description in section 2.2, distribution system plays a very importance role as a part in electrical power system because it is connected closely to the customers and the reliability of the system depends mainly on an efficient distribution system. Normally, the distribution system consists of many types of equipment including overhead line, underground conductor, bus bar, disconnection switch, distribution transformer, and circuit breaker. The demand for electricity has been increased over years due to the present growing domestic, industrial, and commercial load day by day. Hence, the network has been continuously expending to supply power to the customer, and the reliability and quality must be met to satisfy the customer. The distribution system is designed to serve a unidirectional power flow from high to lower voltage. Majority of the cases, the system is designed in radial form even though there are other configurations such as loop, and network system. Each configuration is distinguished through a distinct feeder arrangement and unique type of connection. Electrical power distribution is either three or four wires. In these four wires, 3 wire is for phases and 1 wire for Neutral. The voltage between phases to phase is called Line Voltage and the voltage between phase and neutral is called phase voltage. This forth wire may or may not be distributed and in the same way this neutral may or may not be earthed.

2.3.1 Radial Distribution System

Radial distribution is a system which has only one power source for a group of the load. It is very frequently used due to its simplicity and low cost to construct. Moreover, it is widely preferred in the sparsely populated area. However, the main drawback is poor reliability because all the buses are supplied only from one side, so if a fault occurred in any branch, the downstream will be isolated. The conductor can be overhead or underground, or combination of the both. Behnke et al., (2005) wrote that voltage regulator and capacitor bank can be installed at the input of the feeder or node of the transformer for improving the voltage and power factor along the branches. The length of the feeder is likely in the range of 1.5 to 30 km with the capacity of the distribution transformer in the range of 0.15 to 2MVA. To meet the safety standard requirement, the protection devices are required such as line recloser, sectionalizing breaker, and fuse at the intermediate location along the primary feeder and laterals. Normally, the radial distribution feeder drives the power flow decreasing trend in the downstream toward the end of the feeder. Also, the system is categorized into two types in term of distributed load. The network which is connected to the different load capacity in each node is called discrete load system as shown in Figure 2.2.a, and the network with the same load capacity is called uniform load system as illustrated in Figure 2.2.b.

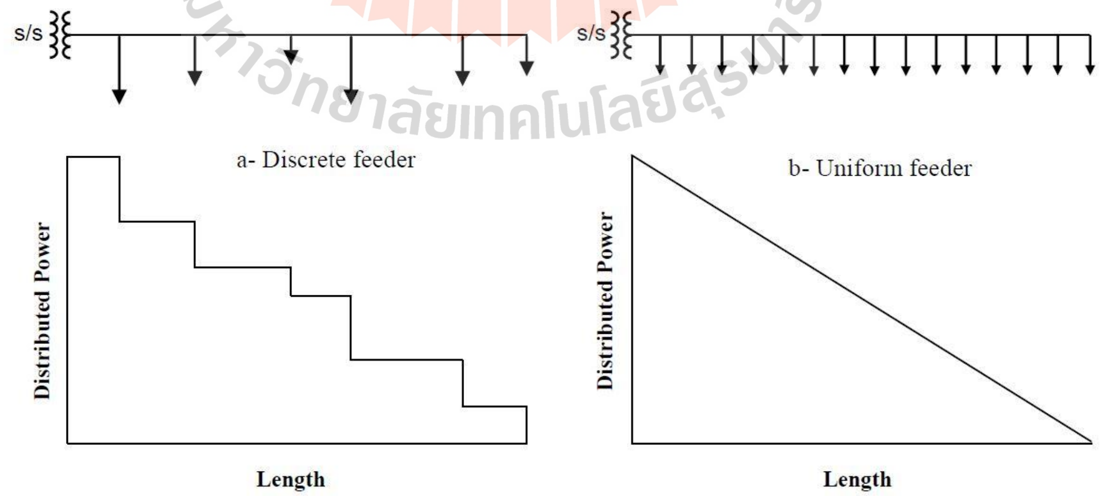

Figure 2.2 Discrete and uniform feeders (Al sabounchi, 2011).

2.3.2 Loop Distribution System

In loop system, all the buses and loads are supplied from two primary feeders. Normally, it is considered the alternative source by switching at the strategic location in case of fault or repairing. The system is used where a higher reliability and continuity of power supply is required. If one source fails to supply, it can be switch manually or automatically, so the loads are fed by another power source with short time interruption. The main disadvantages of this system are high investment cost and more complexity because the more equipment and conductors are required, but the improvement of system reliability is often worth the price.

2.3.3 Network Distribution System

The network system is often used where the highest reliability of power supply is required, so it is usually applied at a high density of load or downtown areas. The loads are fed by many different power sources through the network transformers which are protected the protection devices to clear the network from the faults, and the special limiting currents are also used at a various sensitive location to maintain spreading of the faults (Casazza and Delea, 2010). Furthermore, it is more complex because the system is interlocked together. The high capital cost is the main drawback of this system, but it is compensated with the system reliability.

2.3.4 Power Loss

The loss is unavoidable and it occurs when the electrical power passes through the conductor in the power system. The distribution part contributes to 73% of total losses in the system while only 23% in transmission network (DECC, 2013).

As a result, the distribution network shares the largest losses among the three divisions of power system since it is connected to many loads with a lot of components such as lines, transformers, substations, transformers, switches, circuit breakers, and so on. Moreover, the variety of different connected loads also contributed significantly to the power losses. Two kinds of loss which are considered as the main contribution of power loss. The loss in the conductor due to current flow is equal to the current squared time of resistance of the conductor that is called real power loss. Similarly, reactive power loss is related to the reactance of the conductor, and it is equal to the current squared time of reactance of the conductor. Another loss is the core loss of the transformer that is independent of the current. The loss is occurred due to hysteresis and eddy current in the transformer core, and this loss depends on the material used in the core as well (El Hawary, 2008).

2.3.5 Voltage Drop

Voltage drop is the common phenomenon when the network connected to the different loads and across a long distance because the inductive reactance of the line is increased if the length of the line is increased. Hence, the voltage is dropped especially at the end receiving bus. Voltage drop can be solved by installing capacitors or using a voltage supporter called voltage regulators. Furthermore, the on-site power generation can minimize voltage drop and enhance voltage profile effectively if it is installed with the optimal location and size in the system.

2.4 Distributed Generation

Traditionally, the distribution system has been designed on the concept of one direction flow of power from higher to lower voltage level. The distribution generation (DG) is the new technology development and liberalization of electricity market along with economical and regulatory factors. The increase of power demand, the environmental concern, and the power quality are the reasons of emerging DG in the distribution system. The term of DG refers to the small scale of power generation dispersed in distribution network level, and it is closely connected nearly to the customers or isolated from the power grid (Brown, 2008). Also, Willis, (2000) stated that the efficiency of DG technology is high (40-55%) when compared to the traditional large power plants (28-35%).

2.4.1 Definition of DG

DG has been defined as a small source of electric power generation or storage which is not considered as any part of a central power system and it is relatively closed to the load area. Furthermore, DG has been also cosidered as the small power generation which has a capacity less than 30MW. Chamber, (2001) wrote that DG is likely installed near or at customer sites in order to fulfill specific customer's needs and improve power quality. Currently, there is no consensus on how DG should be exactly defined. Some countries define distributed generation on the basis of the voltage level, whereas others start from the principle that distributed generation is connected to circuits from which consumer loads are supplied directly.

According to conseil international des grands réseaux électriques (CIGRE), DG is defined as all generation units with a maximum capacity of 50MW to 100MW, that is usually connected to the distribution network and that are neither centrally planned nor dispatched. Due to IEEE, DG is considered as the generation of electricity by the facilities that are sufficiently smaller than central power plants, and it is allowed the interconnection at nearly any point in the power system. Moreover, it is also defined as a power producing units at a customer’s site or within local distribution utilities and supply power directly to the local distribution network.

The task of defining the scope of distributed generation has also been taken by many academics. DGs was defined as a small source of electric power generation or storage (typically ranging from less than a kW to tens of MW) that is not a part of a large central power system and is located close to the load (Dondi et al., 2002). Moreover, it is also defined as relatively small generation units of 30MW or less, which are sited at or near customer sites to meet specific customer needs, to support the economic operation of the distribution grid, or both. Some researchers or countries may refer DG as embedded generation while in others it is known as a dispersed generation or decentralized generation. International Energy Agency (IEA) has clarified all different forms as the description in Table 2.1.

Table 2.1 Different terms of DG with the description.

Term	Description
Distributed generation	DG technologies connected closely to loads, except wind turbine.
Dispersed generation	DG including wind turbine
Distributed power	DG and energy storage
Distributed energy resource	DG and demand side management
Decentralized power	DG connected to the distribution system

Table 2.2. DG type based on capacity.

DG types	Ratings
Micro distributes generation	1W - 5 kW
Small distributed generation	5kW - 5MW
Medium distributed generation	5MW - 50MW
Large distributed generation	50MW - 300MW

After the definition and all term of DG has been clarified and described, the type of DG is provided. Moreover, DG type can be classified based on technology and capacity. Shaddi and Santoso, (2016) categorized DG based on capacity into four types are shown in Table 2.2, and it has three type in term of technologies as illustrated in Table 2.3.

Table 2.3 DG type based on technology.

Renewable DG
Modular DG
Combine heat and power (CHP)

2.4.2 Brief History of DG

DG is not a new thing actually because, after ermerging of alternative current in the early 20th century, the energy needs such as heating, cooling, lighting are supplied near the ponit of use. Due to advance technology, large of power plants are constucted far away from the urban area, and the power is transmitted through a transmission line with high voltage level. Then, it is delivered to the customers through the distribution netwok with low voltage level. Some customers or facilities realized that it is economically advantagous to install their own power poducing units because some facilities need high reliablity and continouity of supply.

The technologies of both central generation and DG has been improved. Hence, electrical power generation has been becoming more efficient and less costly. Nowadays, advanced technologies in new material and design for electrical power generation and storage units which including solar photovoltaic panel, micro turbine, gas turbine, fuel cell, supercapacitor, and advancedly digital control have increased the efficiencies and applications for DG in electrical power production iorder to improve quality and stability of the system. Due to the change of electical power market regulation in the whole sale and retails market, it has opened the chances for the customers to install DG to fulfill their own energy needs. Also, it is also the good ways for the utilities to meet power demands in the system.

2.4.3 Technologies of DG

There is various technologies of DG applying in power system nowadays, and the common things of each technology are to increase the effeciency and reduce the cost of operations, installations, and maintenances. Some technologies have been used for a long time ago while others have just created. Moreover, the technologies are categorized into two types. Renewable technologies consist of solar PV, wind turbine, biomass, etc., and non renewable teachnologies include micro turbine, fuel cell, internal reciprocating engine, etc. DG technologies have a significant impact on the selection of location and size to be installed in the network and connected to the loads. Additionally, the DG technologies can be distinguished to dispatchable and non-dispatchable as shown in Figure 2.3. the details of the most popoluar technologies in the current market of DG are provided in next section.

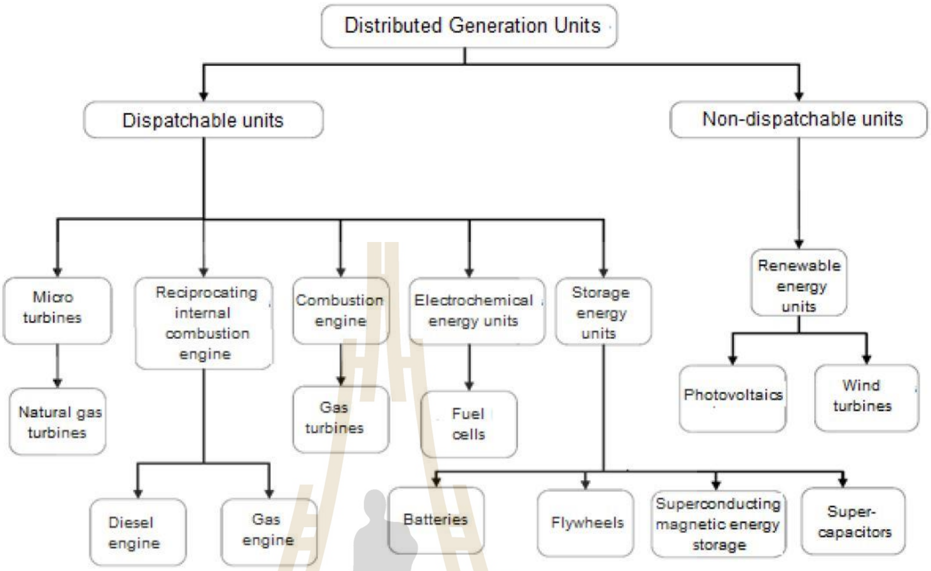

Figure 2.3. DG technologies (Al-Abri, 2012).

2.4.3.1 Solar Photovoltaic

A photovoltaic (PV) cell is made of special materials called semiconductor which is used to convert sun light energy to electrical energy. Each PV cell generates less than one watt of DC power, so the PV cells are connected in serie and paralelle to produce 12V for a panel or module. Similarly, a group of modules is connected in paralelle and series to increase the output of current and voltage in DC. The diode is used to direct the current to flow in one way and converted the power from DC to AC. The capital of PV system is high, but the operating cost and maintenance if lowe if compared with other techonologies. Due to driven advance technology and an increase in manufacturing, the productive cost of PV cell has been decreased steadily over years. PV technology is encouraged and considered as a good choice for DG due to the unlimited availability of sunlight, long life cycle, high modularity and mobility, easy maintainability (since there are no moving parts), very low operation cost, environmentally friendly, ability for off-grid application and short time for design, installation and start up (Osaloni, 2016). The main drawback of this technology is high investment cost and intermittent output.

2.4.3.2 Wind Turbine

The wind turbine is also a renewable energy which uses wind energy to transform into electrical energy. A wind turbine consists of a rotor, blades, generator, drive or coupling device shaft, and nacelle. Similar to PV system, it is required to use converter AC/DC to be connected to the grid. Moreover, the wind turbine has capacity in the range from less than 5 to over 1000 kW, and it is usually connected together to be a wind which can produce power up to megawatts.

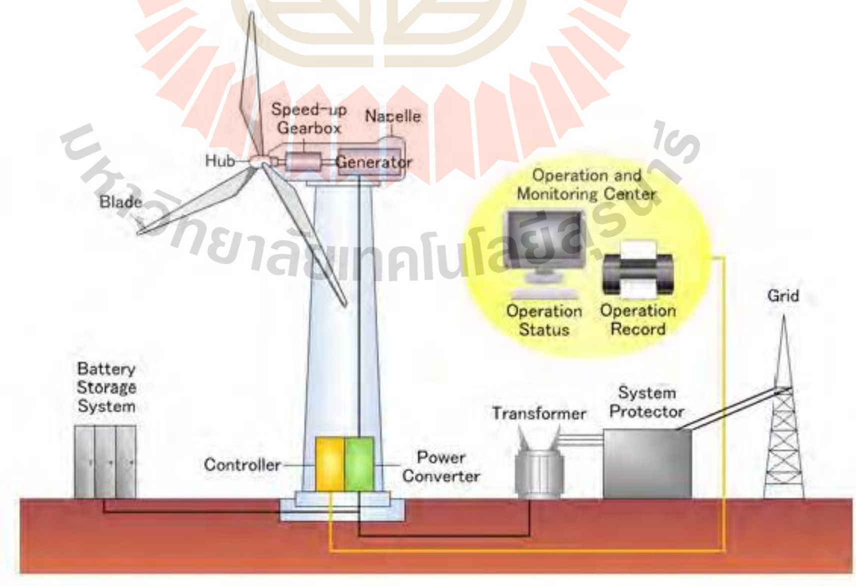

Figure 2.4 Schematic operation diagram of a wind turbine (El-Khattam and Salama, 2004).

Normally, the wind farm is connected to the transmission level, but sometime it can be considered as DG because size and location of some small wind turbine make them be feasible for distribution level (Morita, 2002). A small wind turbine which is operated as a module can be combined with PV and battery systems to serve an area requiring 25–100 kW as shown in Figure 2.4. The main disadvantages of wind turbine technology are high initial cost and intermittency of supply.

2.4.3.3 Micro Turbine

Micro turbines (MC) are the small scale of a turbine engine with the integration of generator using natural gas, propane or fuel oil and power electronics. MC consists of three basin components: a compressor, a turbine generator, and a recuperator. Moreover, MC produces AC power with high frequency with very high rotational speed up to 120, 000 rpm, so it is required to use power electronic to transform the power to a useable level. The capacity of MC is usually in the range from 30 to 200 kW, and it can be combined readily into systems of multiple units to get high output. Also, in some cases, micro turbines can be designed with waste heat recovery equipment to produce chilled water to increase efficiency up to 80% while the emissions of NOx are low when compared to large scale turbines (Zareipour, Bhattacharya, and Canizares, 2004). The merit of (MT) over internal combustion engines is low noise, less frequent maintenance, less vibration, more compact size, lower uncontrolled emissions, and an exemption from air quality permitting in many circumstances.

2.4.3.4 Fuel Cell

Fuel cell is a recent technology which produces electricity from the chemical reaction between oxygen as an oxidant and hydrogen as a fuel without any combustion. Hence, it produces almost no pollutants and has no moving parts (El-Khattam and Salama, 2004). The hydrogen needed in the reaction is obtained from hydrogen rich fuel such as natural gas, propane, or methane from biogases. Also, the reaction produces not only electricity but also water and heat. DC/AC converter is required to transform the power to be connected to the grid because fuel cell generates high current/low voltage DC power. Its application as distributed generation ranges from 1 kW to 3 MW capacity.

Table 2.4 Characteristic of fuel cell types (Mohamed, 2013).

	PEMFC	**AFC**	**PAFC**	**MCFC**	**SOFC**
Electrolyte	Polymer membrane	KOH & H_2O Phosp. Acid	H_3PO_4 Lithium carb.	$LiKaCo_3$ Zirconia	Stabilized
Internal Temp.	85^0C	120^0C	190^0C	650^0C	1000^0C
Efficiency	30%+	32%+	~40%	~42%	~45%
Applications	Car, space	Car, other	DG	Large DG	Very large DG
Installed Cost $/kW	$1,400	$2,700	$2,100	$2,600	$3,000
Advantages	Solid electrolyte reduces corrosion, low temperature, quick start-up	Cathode reaction faster in Alkaline electrolyte, high performance	Up to 850/. efficiency m co-generation of electricity	Higher efficiency, fuel flexibility, inexpensive catalysts	Higher efficiency, fuel flexibility, inexpensive catalysts, solid electrolyte advantages like PEXI

Fuel cells can be used as an electrical power generation technology or in CHP applications. The fuel cell provides efficiency in the range from 40 – 60% of electricity production. This technology is very friendly to the environment due to no pollutants and very less noise, and the high capital cost is the main drawback of this technology. Fuel cell is categorized into five types based on the chemical reaction and their description are described in Table 2.3 (Willis, 2000).

2.4.3.5 Gas Turbine

Gas turbine is a device which transforms the rotational energy to electrical energy, and it comprises of combustor, compressor, and turbine generator. Currently, it is widely used power industry. The maintenance cost is on the lower side than for reciprocating engines. Gas turbines can be noisy and emissions are somewhat lower than for combustion engines, a cost-effective NOx emission-control technology is commercially available in market.

2.4.3.6 Internal Combustion Engine

Internal combustion engine (ICE) is a heat engine where the fuel is burnt in a confined space called a combustion chamber. The reaction of the fuel with oxidizer produces high pressure and temperature to expand. Normally, ICE is referred to the reciprocating engine in which combustion is intermittent. Noise and pollution are the main barriers to this technology. However, fast start up and portability are the main advantages of ICE.

2.4.4 Impacts

Traditionally, the distribution systems are designed to deliver the electrical power to the load in one direction. The presence of DG in the system obviously has the effects to the system such as power flow, voltage regulation, loss, reliability, and protection system because the installation of DG creates a new source in the system and it causes to change the direction of power flow. When the DG power is more than the downstream load, it sends power upstream reversing the direction of power flow, and at some point between the DG and substation, the real power flow is zero due to back flow of power from DG (Philip and Barker, 2011). Next section details each impact of DG in the distribution network.

2.4.4.1 Voltage Regulation

The voltage of distribution system can be regulated by load tap-changer transformers, voltage regulators, and shunt capacitors. When DG is connected to the system, power flow of real and reactive power, as well as voltage magnitude, is also changed. Nevertheless, the presence of DG can provide either advantages or drawback to the system. The voltage profile is improved well if DG is placed at the optimal location, but it causes to occur voltage fluctuation and more loss which are the negative effects of DG. DG impact on the primary feeder is negligible for a small unit of range (< 10MW). However, if the aggregate capacity increases to critical thresholds, then voltage regulation analysis is required to make sure that the feeder voltage will be fixed within suitable limits (Fernández, 2011).

2.4.4.2 Loss

The presence of DG in the distribution system has impacts on the loss of the system. DG can provide both real and reactive power to the system, while capacitor banks inject only the reactive power. When a DG is installed in any optimal location of any feeder, the overall losses of the system is reduced significantly. Moreover, if a small capacity of DGs is connected to the system, it will show the important positive effects on loss reduction and it is a great benefit for the utilities. They utilities have to consider about thermal capacity of the lines and feeders because if high units of DG is added, it can be over the capacity of the lines (Fernández, 2011).

2.4.4.3 System Security

Distributed Generation causes an increase in short-circuit current. When a short-circuit fault occurs, the fault current is supplied from both the power system and DG to the fault point. If the total fault current exceeds the capacity of the feeder circuit breaker, the fault cannot be clear, and so continues. Increase in fault current deteriorates sensitivity to faults, depending on the location of the fault, the sensitivity of the relay system is liable to deteriorate. When fault current decreases on the feeder at the substation by supplying fault current from DG, the relay system either may not be able to detect the fault or may be slow to detect it (Osaloni, 2016; Borges and Falcao, 2006).

2.4.4.4 Power Quality

Distributed Generation can also result in excess voltage. Additionally, an SVR compensates the voltage midway along the line in heavy power-flow or long transmission lines. A load of each feeder should be balanced proportionally to utilize these voltage control systems. If there are many DG connections concentrated on a specific line, the gap in the power flow between feeder lines increases because of the back-flow from the DG. There is of particular concern when generating systems that depend on natural conditions, such as wind power or solar photovoltaic generators, are interconnected to the local system (Borges and Falcao, 2006)

2.4.4.5 Power Reliability

Obviously, DG has the positive impacts on the system reliability if it is placed and sized optimally in the system. For instance, DG is the back-up generator when the main power supply is interrupted. The utilities can install DG for improving the restoration capability of the distribution networks, and DG can eliminate network constraints (voltage drop or feeder loading) during the restoration process (Neto, Silva, and Rodrigues, 2006).

2.4.4.6 Environment

The technologies of DG such as solar, wind, biomass, and other low carbon emissions are so friendly to the environment because these DGs technologies produce almost no pollutants. The increase of DG presences in the distribution system is the great positive impacts for the environment and it is the important penetration of renewable energy in electrical sector in the future in order to reduce greenhouse gases (GHGs) emission to prevent from climate change and global warming. Towards eco-friendly operation improvement, there is need to program the central controller (CC) to make operational decisions based on the net lowest emission production, in view of both local emission and displaced emission from micro sources. The structure of emission tariffs is a combined function of season, time and location so the tariffs would be most attractive at worst pollution time and location. This would send a signal to the central controller to operate the micro source optimally for minimizing emission. In lieu of this, existing environmental regulation should be strictly adhered to (Osaloni, 2016).

2.4.5 Future of DG

DG will play a more important role in the future of electricity sector. The energy of informatin administration (EIA) reported that the DG's constribution to electricity is predicted to increase drastically and renewably generated electricity will account for 12.5% of total U.S. electricity generation in 2030 because DG provides the high potential of benefits to offset the traditional distribution system. Many reseach papers have investigated and proved the great importance and the application of DG in distribution networks in loss redction, reliability and quality improvement, and environmental friendliness.

However, the DG integration in the system is complex problem which require the the technical analysis and studies of its application on reliable and enocomic operation in the system. In the future, the distribution will be fed by many small generation units which connect directly closely to the system. DGs can be modular, a small system which can be combined with management and energy storage system to enhance the operation of the distribution system. In environemal point of view, DG has been consdered clean, relaible, and secure. If the efficient planning and optimal operation of the power grid are achieved, it will be possble for DG to play the greater roles in the future in contributing to energy efficiency improvement, distribution investment cost reduction, and power quality enhancement.

Meanwhile, the efficient constribution of a rising share of DG also requires the network innovation.

2.5 Literature Review

The emerging and increase of DG integration in the electrical power system is a result of reliability and quality of power needs, electricity marker privatization, environmental protection, and technology development. The lack of technological knowledge and uncontrolled installation of DG in distribution network during the last two decades brought into some problems and challenges to the system. Such problems are the inevitable bidirectional power flow in the modern distribution networks, in contrast to unidirectional power flow from higher to lower voltages, and the very important problems of voltage drop and power losses (Vita, 2016). Many academics and researchers have studied the occurred problems and developed various techniques as well as methodologies for DG application in the electric power system to get high benefits and avoid any technical problems. The optimum installation of DG in the system can improve voltage profile and minimize power losses in distribution network effectively and economically. The appropriate solution for DG deployment can be obtained via optimization methods to maximize the benefits from DG. Several methods both of conventional and artificial intelligent (AI) techniques have been presented in determining the optimal location and size of DG. The optimization methods can be classified into deterministic methods such as analytical and SQP methods and heuristic methods such as genetic algorithm (GA), artificial bee colony (ABC), and particle swarm optimization (PSO), etc. The core purpose of DG application optimization is to locate and size optimally of DG in the system in order to minimize the power loss. Meanwhile, voltage profile, reliability improvement, and cost minimization have also been included.

Gandomkar, Vakilian, and Ehsan (2005) used Hereford ranch algorithm (HRA) to determine the location and capacity of DG while minimizing the distribution power loss as the objective function with the condition that number and capacity of DG were known. The parent selection algorithm for generating offspring affects the ability of GA in three aspects: finding a correct solution for a variety of the problems; preserving diversity to prevent premature convergence; and improving the convergence time. To overcome the defects from the existing GA, the authors applied HRA to search for the optimal size and placement of DG in the distribution feeders. HRA uses sexual differentiation and selective breeding in choosing parents for genetic strings. In terms of both solution quality and a number of iterations, the proposed HRA performed better than individual GA.

Acharya, Mahat, and Mithulananthan, (2006) developed an analytical method to find the optimal capacity of DG. The optimal size of DG was calculated using direct equation derived from the sensitivity factor equation. Also, the methodology based on the formula on an exact loss formula was applied to determine the optimal location which provided minimum loss. The method carried out the load flow to times, for the base case without DG and with DG in regarding of considering only a single DG which injected only real power.

Alhajri and El-Hawary (2007) determined the optimal location and capacity of DG with a new method based on the fast SQP. The DG optimization problem was formulated as a constraint nonlinear programming subject to nonlinear equality and inequality constraint in addition to boundary restriction imposed on the system. Real power loss minimization was the objective function in the aim of loss reduction and voltage profile improvement while all possible combinations for allocating DG were investigated to find the best location of DG. Integrated single and multiple DG units were discussed where DG units were modeled as a negative load delivering the real and reactive power to the distribution network.

Alinejad-Beromi at al. (2007) proposed a method for DG application in the distribution system in term of power loss minimization and voltage profile improvement. GA was used to optimize the problems and all constraint such as feeder capacity limits, feeder voltage profile, and three phase short circuit current in the network nodes were considered. The planning study period was 20 years and the DG units under consideration range between 100 to 500KVA with a 100 steps. The maximum level of DG penetration was 20% of total power demand.

Subrahmanyam and Radhakrishna (2009) used a simple algorithm which power loss was the objective function to determine the optimum location and size of DG in unbalance radial distribution network in the aims of voltage profile improvement and loss reduction. The algorithm was evaluated in 25 and 37 buses of unbalance radial distribution network.

Moradi and Abedinie (2010) developed a new algorithm which was the combination of GA and PSO. The combined method was formulated as a multi-objective constrained optimization problem that aimed to obtain the optimal size and location of DG in radial distribution system while power loss minimization was the objective function considering voltage profile improvement and system constraints. Moreover, GA was used to find the optimal location of DG, while PSO was applied to determine the optimal size. The proposed method achieved a better solution quality with fewer iterations when compared to cases where either method was applied alone. Nevertheless, long computation time is a drawback of this proposed technique.

Sedighizadeh et al., (2010) presented a new advance method for optimal allocation and size of DG in the radial distribution system. The optimum solution could be obtained by introducing the power losses and voltage profile as the variables into the objective function. Also, PSO and clonal selection algorithm optimization (CLONALG) were applied to solve the optimization problem in previous studies. In this work, the combination of PSO and ClONALG which was called PCLONALG was used to get the superior solution. The method was tested with 13 buses of radial distribution network considering single and multiple DGs. The obtained result showed that the PCLONALG method had a higher ability to find the optimum solution when compared to PSO and CLONALG in term of quality of solutions and number of iterations.

Abu-Mouti and El-Hawary, (2011) presented a heuristic method to determine the optimal siting and capacity of DG in distribution network while the optimization objective was the total power loss minimization. The problem was divided into two sub problems and each part was treated independently. The author employed an effective sensitivity analysis based on power flow in the first portion to determine the best location to install DG while the optimal size was obtained by using curve fitted technique.

Abu-Mouti and El-Hawary (2011) proposed ABC which is a meta-heuristic optimization approach to determine the optimal size and location of DG in the distribution system. The new approach was mathematically formulated as a constrained nonlinear optimization problem where total power loss minimization was the objective function to be minimized, subject to nonlinear equality and inequality constraints. The DG capacity was bound between 10% and 80% of the total load and approximate to discrete values with a 100 step interval between sizes. Moreover, the power factor of the DG was set to operate at practical values including at unity, 0.95, 0.90, and 0.85 toward the optimal results.

Aref et al., (2012) studied the effects of the significant parameters such as reliability, loss reduction, and efficiency to optimally enhance the cost parameter including loss reduction, voltage profile improvement, environmental effects, fuel price, and cost of predicting a load of each bus. DIGSILENT software was used to compute power flow to get power loss. The change of weight of each parameter in the destination function of GA lead to change the location and size of DG in the network as well.

Nadhir, k., Chabane, D., and Tarek, B. (2013) applied a novel meta-heuristic algorithm inspired by the behavior of fireflies flashing. Networks tested IEEE69-bus and IEEE33-bus are used to evaluate the effectiveness of this method. The results are compared with those obtained by genetic algorithm (GA) to IEEE69-bus, and Shuffled frog leaping algorithm (SFLA) for IEEE 33-bus.

Pandy and Bhadoriya (2014) used PSO to find the optimal location and size of DG while power loss minimization was the objective function. A two stage methodology was practiced for the optimal DG placement. In the first stage, power system analysis toolbox (PSAT), an open source MATLAB software for analysis and design of small to a medium size electric power system for power flow. In the second stage, PSO was applied to find the optimal size and placement of DG in the distribution system. The effectiveness of the proposed method was evaluated through IEEE 16 bus test system.

Guerriche and Boutir (2015) applied PSO to find the siting and size of DG in 33 buses of the radial distribution network. In this study, loss minimization was the objective function, and the study was evaluated under three kinds of load levels. The light load which had 50% from the full load and heavy load which equaled to 150% of full load in order to see how the DG could overcome with the load variation.

Alinezhad, Bakhoda, and Menhaj (2015) applied various AI types to optimize the location and size of DG for performance and effectiveness comparison with the multi-objective optimization model. The multi-objective of cost function was used to reach all the objectives including optimal placement and size of DG, loss reduction, voltage profile improvement, reliability increase, and decreasing of DG installation cost. Three AI techniques of PSO, GA, and GSA were applied to examine the problems. The simulation results indicated the efficiency of the applied methods in solution finding and dominancy of GSA over PSO and GS in the optimal placement of DG.

Mehta et al., (2015) presents the analysis for the selection of the best type of DG unit among different categories and its optimal location that can enhance the voltage stability of distribution network with simultaneous improvement in voltage profile. Voltage sensitivity index and bus participation factors derived from continuation power flow and modal analysis, respectively, are used together for voltage stability assessment and placement of DGs.

Prakash and Khatod, (2016) presented the analytical method in optimal location and size of DG in radial distribution systems. The objective of the proposed method was to minimize the system loss. Firstly, the method identified an order of bus to be compensated by solving the maximum power loss saving with the placement of single DG unit in the system. The basic and suited analytical expression was derived to compute the optimal size of DG unit and corresponding loss saving by considering the variation in the magnitude of the branches current due to the installation of DG unit. The developed method was equally applicable to optimize the size and location single as well as multiple DGs units for the balanced radial distribution network. The proposed method was evaluated with 33 buses of the radial distribution network.

A study conducted by Lorestani et al., (2016) proposed an analytical heuristic method (AHM) for solving the optimal placement and size of multiple DG to achieve high loss reduction and voltage profile improvement in large scale distribution networks. The proposed method was based on the improvement of loss sensitivity factor method (LSF). AHM used PSO to optimize the real and reactive power generation of DG and applied LSF to identify the most appropriate location of DG. The simulation results showed that the proposed approach was more effective that all the analytical method which are able to solve the multiple DG applications, including LSF and improve analytical (IA) method. Moreover, it was shown that DG which injected both real and reactive power provided the better solution regarding of loss reduction and voltage improvement than DG which injected only real power in case of two or three DG cases.

Uniya and Kumar (2016) made the comparison of optimal DG location between sensitive based and optimization based approach. The first approach of voltage sensitive index (VSI) and index vector (IV) which were applied to figure out the most sensitive bus which needed to install DG in the system with the optimal size of DG that provided the less loss. In the second approach, various AI methods were used to point the location and capacity of DG such as cuckoo search algorithm, gravitational search algorithm, GA, and PSO. The achieved results illustrated that the location of DG from sensitive based was the same to optimization based. However, the sizes of DG from sensitive based were different from optimization based. The obtained sizes were comparable. The obtained results showed the heuristic techniques proved to be more accurate, and PSO provided the solution in the minimum time. 33 buses of radial distribution network was the tested case to evaluate the proposed method.

Dinakara Prasad Reddy, Veera Reddy, and Gowri Manohar (2017) proposed whale optimization algorithm (WOA) which is a very recent meta-heuristic optimization technique used to find the optimal location and size of DG in the radial distribution system. The WOA was evaluated on IEEE 15, 33, 69, and 85 bus test systems. Furthermore, the proposed algorithm was deal with the different types of DG and compared with voltage sensitivity index method. The better result was achieved with WOA compared with other algorithms. The obtained results were illustrated that the type of DG that injected both active and reactive power provided the best solutions when compared to those of other DGs.

Vita (2017) developed a decision making algorithm for the optimization of DG application in distribution system. The algorithm that is very flexible to changes and modifications can define the optimal location for a DG unit (of any type) and can estimate the optimum DG size to be installed, based on the improvement of voltage profiles and the reduction of the network's total real and reactive power losses. The proposed algorithm has been tested on the IEEE 33-bus radial distribution system.

The obtained results are compared with those of earlier studies, proving that the decision-making algorithm is working well with an acceptable accuracy. The algorithm can assist engineers, electric utilities, and distribution network operators with more efficient integration of new DG units in the current distribution networks.

Ali, Abd Elzim, and Abdelaziz (2017) proposed ant lion optimization algorithm to find optimum location and capacity of renewable DG for various distribution system. First the most candidate buses for installing DG are suggested using Loss Sensitivity Factors (LSFs). Then the proposed ALOA is employed to deduce the locations of DG and their sizing from the elected buses. The proposed algorithm is tested on 33 and 69 bus radial distribution systems. The obtained results via the proposed algorithm are compared with others to highlight its benefits in reducing total power losses and consequently maximizing the net saving. Moreover, the results are introduced to verify the superiority of the proposed algorithm to improve the voltage profiles for various loading conditions. Also, the Wilcoxon test is applied to confirm the effectiveness of the proposed algorithm.

In optimization literature, almost no any algorithms which logically prove no-free lunch theorem (Wolpert and Macready, 1997) for solving all the optimization problem. Nevertheless, WOA which is a novel nature inspired meta-heuristic optimization algorithm was proved to be usable for all optimization problems. To the best knowledge of authors, WOA has not been used in literature for real power loss minimization in DG optimization application.

2.6 Chapter summary

This chapter presented the general introduction of the electrical power system which consisted of three parts including generation, transmission, and distribution with the special focusing on distribution section. Then, this was followed by a detailed overview of DG definitions, history, technologies, impacts, and its future. Next, the works of other authors who worked on DG application optimization was presented and discussed. A variety of optimization techniques used to solve DG optimization problems were investigated. Also, most of the proposed method used to solve the problems considered a single objective function which was total power loss minimization considering loss reduction and voltage profile improvement.

CHAPTER III

METHODOLOGY AND PROBLEM FORMULATION

3.1 Introduction

This chapter presents the problem formulation including the general form of optimization procedure and system constraints to which the objective function is subjected to are also defined here. Both equality and inequality constraints are defined. Moreover, the mathematical formulation expressions of loss calculation are presented, while the detail descriptions of AI techniques used to determine the optimal location and size of DG in the distribution network are provided.

3.2 General Form of Optimization

An optimization problem can be mathematically defined as the minimization or maximization of a function (called the objective function) while satisfying a number of equality and/or inequality constraints on its variables (Nocedal and Wright, 1999). The general form of optimization problem can be formulated as:

$$Minimize\ f_i(x,u) \qquad i = 1, 2, , ..., N_{obj}\,, \tag{3.1}$$

$$Subject\,to\ \ g(x,u) = 0, h(x,u) \le 0, \tag{3.2}$$

where,

f_i is the objective function i,

N_{obj} is the number of objective function,

g is the equality constraints,

h is the inequality constraints,

x is the vector of dependent variables, and

u is the vector of independent variables.

The kind of optimization that has only one objective function is called a single-optimization problem. On the other hand, a multi-optimization problem has more than one objective function.

3.2.1 Objective Function

The main purpose of this thesis is to find the optimal size and location of DG in the radial distribution system to minimize active power loss and improve voltage profile. DG is considered as an active power production which operation in unity power factor at a particular voltage. The loss can be obtained by computing the power flow between two buses as is illustrated in Figure 3.1 and the single-objective function for loss minimization can be written as the following equations.

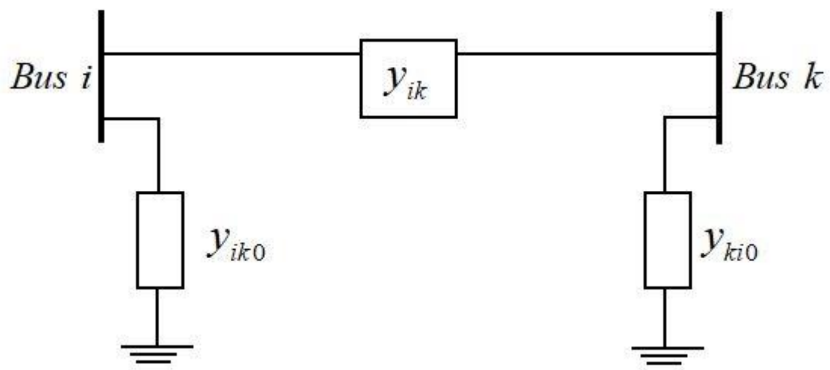

Figure 3.1 Diagram of power flow between two buses.

Where V_i and V_k are the bus voltage at bus i and k respectively. The power flow between buses *i* and *k* at bus *i* is given as;

$$S_{ik} = P_{ik} + Q_{ik} \text{ ,} \tag{3.3}$$

$$S_{ik} = V_i I^*_{ik} \text{ ,} \tag{3.4}$$

$$S_{ik} = V_i (V^*_i - V^*_k)^* Y_{ik} + V_i V_i^* Y_{ik0} \text{ .} \tag{3.5}$$

Similarly, the power flow of between buses *k* and *i* at bus *k* is given as;

$$S_{ki} = V_k (V^*_k - V^*_i)^* Y_{ki} + V_k V_k^* Y_{ki0} \text{ .} \tag{3.6}$$

Hence, the loss between these two buses is the sum of power flow in Equation 5 and 6.

$$S_{Total\,loss} = S_{ik} + S_{ki} \tag{3.7}$$

The total power loss in a system is obtained by summing all the power flow of bus. The power loss in the slack bus can be obtained by summing the power flow at the terminated bus (Anmaka, 2012). In this paper, the reactive power loss is neglected, so the objective function of total real power loss reduction is obtained as;

$$F_{Loss} = real\left(\sum_{i=1}^{n} S_{i\,Total\,loss}\right) \tag{3.8}$$

where,

n is the number of the bus branches, and

$S_{Total\,loss}$ is the total complex power loss.

3.2.2 System Limit Constraints

The system variable constraints are considered as inequality constraints which comprise of voltage magnitude, and real power injection of DG. These variables are optimized and they are limited to be within the constraints during the optimization process. The system variable constraints are expressed as,

$$V_{i\min} \le V_i \le V_{i\max}\,, \tag{3.9}$$

$$V_{\min,DG} \le V_{DG} \le V_{\max,DG}\,, \tag{3.10}$$

$$P_{\min,DG} \le P_{DG} \le P_{total\,demand}\,. \tag{3.11}$$

where,

V_i is the voltage magnitude at bus *i*,

V_{DG} is the voltage magnitude at bus with DG,

$P_{Total\,demand}$ is the total real power demand in the system, and

P_{DG} is the real power generation of DG.

3.2.3 Power Balance Constraints

Power balance is given by nonlinear power flow equations, which state that the sum of complex power flows at each bus in the distribution system injected into a bus minus the power flows extracted from the bus should equal zero. The power flow considering DG integration in the system and it is operated in unity power factor without reactive power generation ($Q_{DG} = 0$) (Pandy and Bhadoriya, 2014). The well-known basic load flow equations are written as,

$$S_i = P_i + JQ_i = V_i . I_i^* , \tag{3.12}$$

$$S_i = V_i \sum_{k=1}^{n} V_k Y_{ik} = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \angle(\delta_i - \delta_k + \theta_{ik}), \tag{3.13}$$

When real and imagination parts are resolved, then the power flow equation without DG can be written as,

$$P_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \cos(\delta_i - \delta_k + \theta_{ik}) = P_{G,i} - P_{D,i} , \tag{3.14}$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \sin(\delta_i - \delta_k + \theta_{ik}) = Q_{G,i} - Q_{D,i} , \tag{3.15}$$

The basic power balance equations are:

$$\sum_{k=1}^{n} P_{G,i} = \sum_{k=1}^{n} P_{D,i} + P_L , \tag{3.16}$$

$$\sum_{k=1}^{n} Q_{G,i} = \sum_{k=1}^{n} Q_{D,i} + Q_L , \tag{3.17}$$

The final power flow equations for a distribution system with DG are:

$$\sum_{k=1}^{n} P_{G,i} + \sum_{k=1}^{n} P_{DG,i} = \sum_{k=1}^{n} P_{D,i} + P_L , \tag{3.18}$$

$$\sum_{k=1}^{n} Q_{G,i} = \sum_{k=1}^{n} Q_{D,i} + Q_L , \tag{3.19}$$

The final power flow equations for a distribution system with DG are:

$$\sum_{k=1}^{n} P_{G,i} + \sum_{k=1}^{n} P_{DG,i} - \sum_{k=1}^{n} P_{D,i} - P_L = 0, \tag{3.20}$$

$$\sum_{k=1}^{n} Q_{G,i} - \sum_{k=1}^{n} Q_{D,i} - Q_L = 0. \tag{3.21}$$

where,

P_i, Q_i are real and reactive power flow at bus *i*,

$P_{D,i}, Q_{D,i}$ are real and reactive demands at bus *i*,

V_i, V_k are voltage magnitudes at bus *i* and *k*,

$P_{DG,i}$ is the real power generated by DG at bus *i*,

δ_i, δ_k are voltage angles at bus *i* and *k*,

Y_{ik} is the magnitude of the *ik*th element in bus admittance matrix,

θ_{ik} is the angle of the *ik*th element in bus admittance matrix, and

n is number of the total buses.

3.3 Optimization Techniques

Up to now, many intelligent search techniques have been proposed and developed to solve the optimization problems which are complex problems instead of using traditional method due to their accuracy and robustness. In this thesis, four algorithms are applied to solve the optimization of siting and capacity of DG in the distribution network. The brief details of the algorithm are provided in this section.

3.3.1 Genetic Algorithm

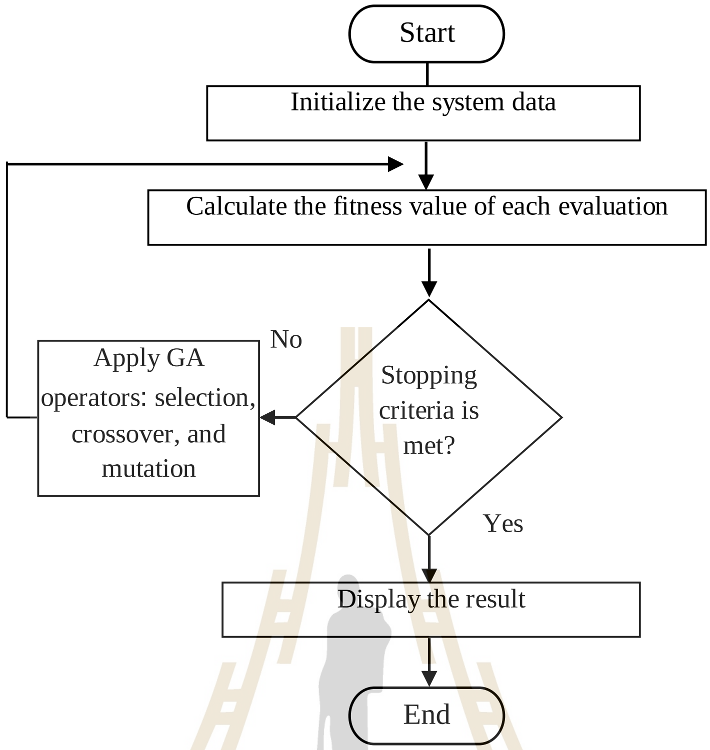

Figure 3.2 Flowchart of the GA.

There are many optimization algorithm techniques for solving the optimization problems. Due to the limitation of classical optimization methods in finding global minimum value, the heuristic optimization methods are widely used because of their reliability, flexibility, and robustness in seeking optimum value in recent years (So and Li, 2000). GA was proposed by John Holland in 1975; moreover, it can find the global optimal solution in complex multi-dimensional search space, and it is a heuristic search method which mimics the biological process of natural evolution such as mutation, crossover, selection, etc., (Pham and Karaboga, 1998). Like others methods, GA needs the initial value and randomly generates the solutions to find the best fitness value (Haibo, Lizi, and Fanling, 1998; Leeton et al.). The working procedure of GA is illustrated in Figure 3.2.

3.3.2 Artificial Bee Colony

Artificial Intelligent techniques can be obtained from natural behavior or phenomenon of animals such as fish, ants, and birds. Currently, a new intelligent search algorithm which mimics the natural behavior of honey bee swarm in searching food sources is called bee algorithm and it was considered as an efficient method in solving optimization problems as other swarm-based intelligent approaches (Karaboga and Basturk, 2007). It was introduced by Karaboga in 2005. The food sources location which foraged by a honey bee represent a feasible solution of the optimization problem and the amount of nectar and pollen of the food sources represent the fitness value of the associated solutions. A bee colony is divided into employed bees, onlooker bees, and scout bees. Employed bees represent the first haft of the colony and the second haft is the onlooker bees. The employed bees whose food sources were exhausted to become scout bees. In the ABC optimization process, it includes the initial phase, employed bee phase, onlooker bee phase, and scout bee phase (Hussian & Roy, 2012).

Initial phase: the numbers of feasible solutions is randomly generated by the following formula:

$$X_{ij} = X_{ij\min} + rand(X_{ij\max} - X_{ij\min}), \tag{3.35}$$

where,

$j = 1, 2, \ldots\ldots, D$. D is the dimension of the problem,

X_{ij} is the jth dimension parameter of the solution X_i,

$X_{ij\max}, X_{ij\min}$ are the upper and lower bounds respectively for dimension *j*, and

rand is the random number between 0 and 1.

Employed bee phase: the employed bees search the food source which is the solution X_k with dimension j in search space from one place to another better place which is the new feasible solution X'_{ij} as shown in Equation 3.35. The best food source location is kept in the memory.

$$X'_{ij} = X_{ij} + R_{ij}(X_{ij} - X_{kj}), \tag{3.36}$$

Where,

$j = 1, 2, ..., D$ and $k = 1, 2, ..., N_e$ are randomly generated ($k \neq i$),

X'_{ij} is the *j*th dimension parameter of candidate solution of X'_i,

X_{kj} is the *j*th dimension parameter of the feasible solution, and

R_{ij} is a random number between −1 and 1.

The fitness value of the feasible solution can be calculated by the formula in Equation 3.37.

$$fit_i = \frac{1}{1+f_i}, \tag{3.37}$$

where,

fit_i is the fitness value of the feasible solution and

f_i is the objective function.

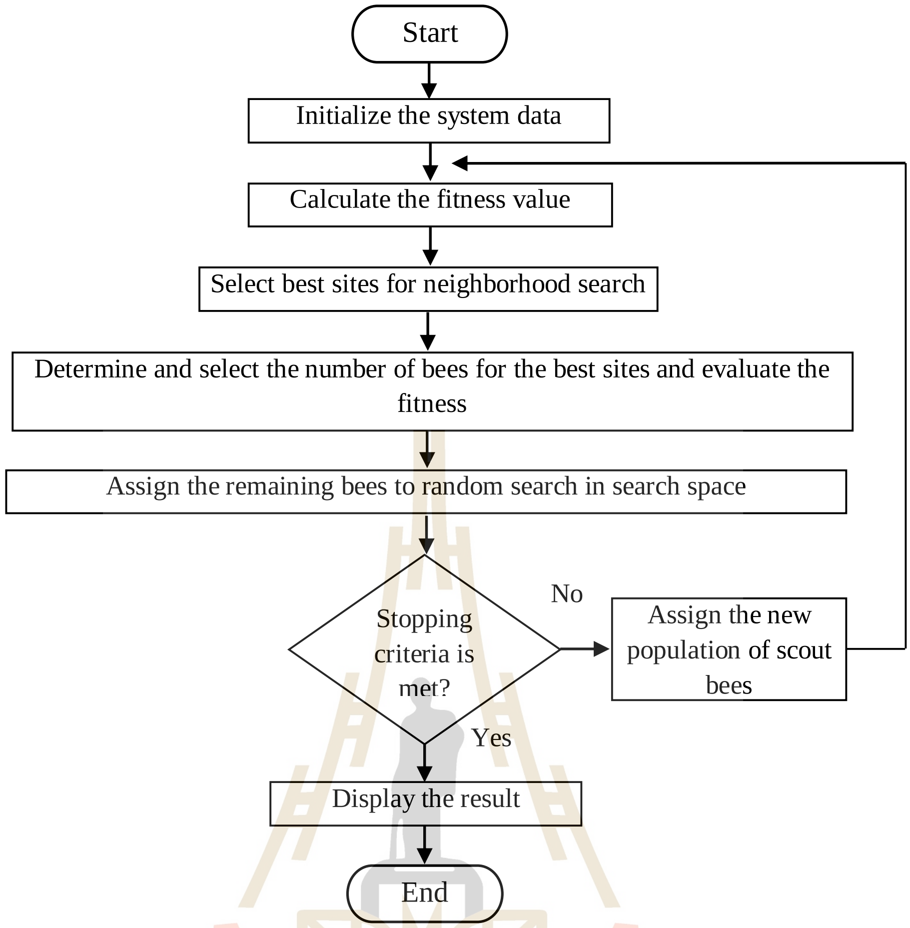

Figure 3.3 Flowchart of ABC algorithm.

Onlooker bee phase: The employed bees share the information of the food source to the onlooker bees waiting on the hive by the special dace which is known as "waggle dance" and then onlooker bee chooses a food source which is a solution by probability depending on the information from employed bees (Sumpavakup, Srikun, and Chusanapiputt, 2010). The probability is given as;

$$\eta_{fit,i} = \frac{fit_i}{\sum_{n=1}^{N_e} fit_i}. \tag{3.38}$$

where,

fit_i is the fitness value of the solution.

Scout bee phase: Every bee colony has scouts which are considered as the colony's explorers. Also, the explorers don't have any guidance to find the food sources. Eventually, the scouts can discover rich in entirely unknown food sources. Nevertheless, the artificial scouts can have rapid discovery in a feasible solution. When the food source is abandoned and the scout bees find a new food source without any guidance with Equation 3.38. The working procedure of ABC is shown in Figure 3.3.

3.2.3 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is the most popular one among the most recent intelligent optimization search methods. It was proposed by Eberhart and Kennedy in 1995 (Guerriche and Bouktir, 2015). It was imitated the behavior of individual swarms which are a flock of bird, school of fish and other insect groups. PSO is the intelligent method which is inspired by individual movement in the group to share the information with each other in order to increase the efficiency of the group (Sinuphun et al., 2011; Jafari, Tabatabaei, and Boushehi, 2016). Each particle is moved based on best personal position (Pbest) and best global position (Gbest) through the information. Moreover, PSO uses the parallel computation method to search and each individual corresponds to the candidate solution of the problem in each iteration. Current speed, previous experiences, and information of its neighbor are the thing which leads to getting the optimum point. In n-dimensional search space, speed vectors represent as the position and individual velocity which participant i and its velocity can be modified by the following equations and the working of PSO can be described in

Figure 3.5. The mathematical expression of the algorithm is also expressed in the following equations.

$$x_i^{(k+1)} = x_i^k + v_i^{(k+1)} \tag{3.39}$$

$$v_i^{(k+1)} = v_i^k + \alpha(\left(x^{Pbest} - x_i^k\right) + \beta\left(x^{Gbest} - x_i^k\right) \tag{3.40}$$

Where,

x_i^k is the current individual position of particle *i* at iteration *k*,

v_i^k is the velocity of particle i of the previous vector at iteration *k*,

α, β are random number between [0 1],

x^{Pbest} is the personal best position of a particle,

x^{Gbest} is the global best position of the particle.

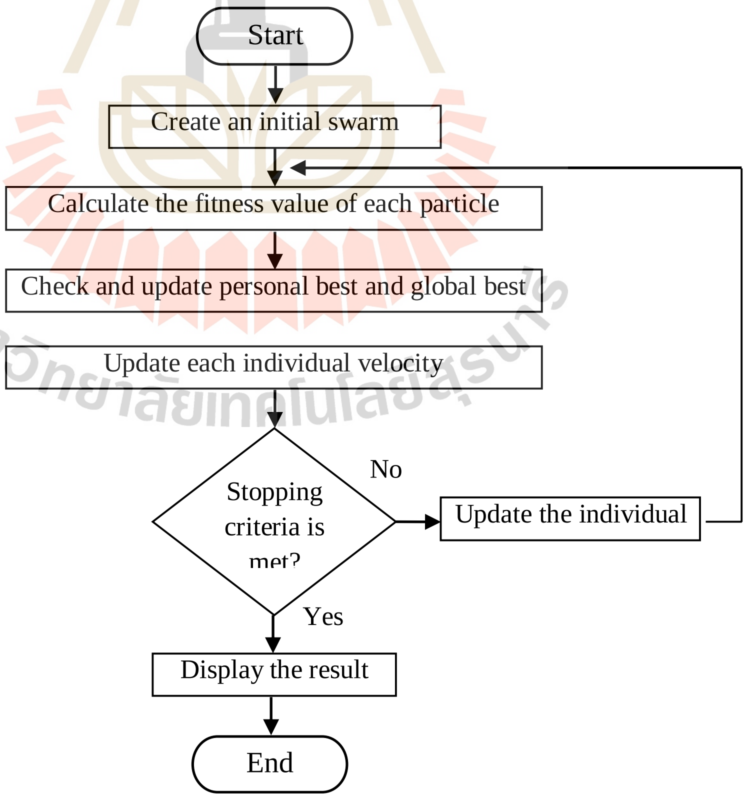

Figure 3.4 Flowchart of PSO algorithm.

3.3.4 Whale Optimization Algorithm

Meta heuristic optimization algorithms are becoming more and more popular in engineering application since it is easy to implement, do not require gradient information, can bypass local optima, can be utilized in a wide range of problem covering a different discipline, and . Similar to the algorithms based on swarm intelligence, rely on a simple concept. WOA is the most recent meta-heuristic optimization search techniques which have just proposed by Seyedali Mirjalili and Andrew Lewis in 2016. It is an intelligent search method which mimics the prey hunting behaviour of a humpback whale.

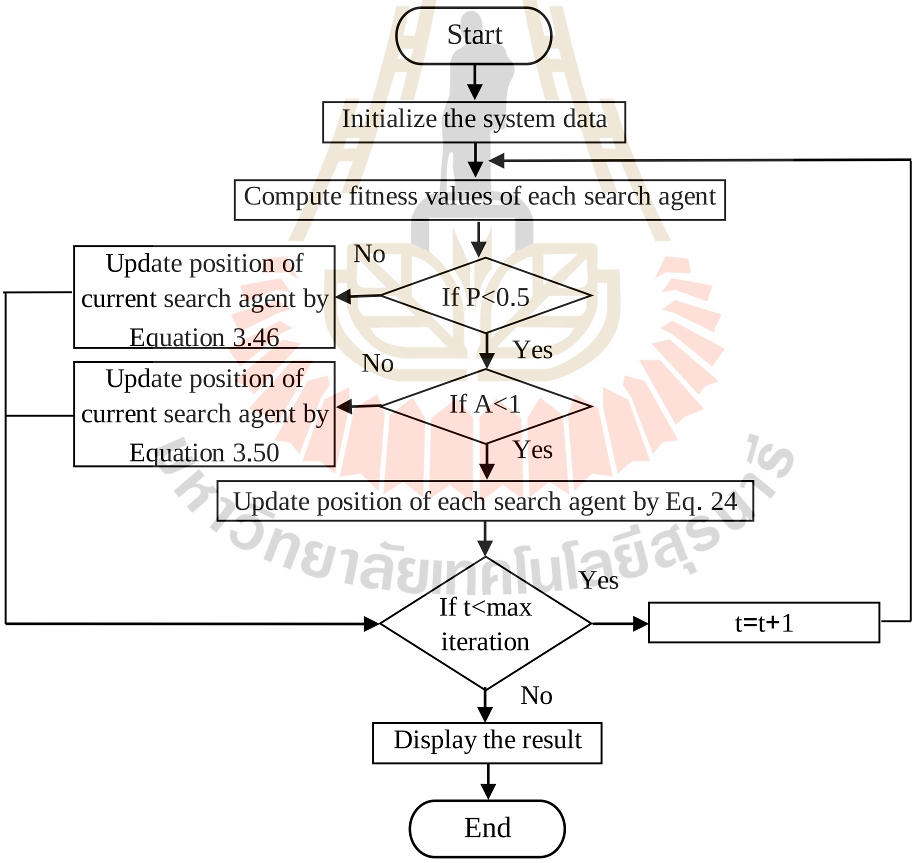

Figure 3.5 Flowchart of WOA.

The whale is considered as an intelligent animal in the world with motion (Dinakara Prasad Reddy, Veera Reddy, and Gowri Manohar, 2017). Humpback whale is the biggest mammals in the sea and it is also a predator which hunts small fish as its prey. Moreover, the whale is the animal which never sleeps at all in its whole life because it needs to breath from the surface of the ocean and the only haft of its brain sleeps [26]. Naturally, humpback whale hunts the small fishes which are closed to the ocean surface by producing the bubble. [27] This hunting behaviour is called bubble-net feeding. When it encounters the prey, it produces bubble circularly or in a spiral shape around the prey and swims up toward the surface as shown in [12]. The mathematical modelling of WOA can be described in three operators [28], [29]. It includes encircling prey, bubble -net hunting, and search for prey, and the flowchart of WOA is shown in Figure 3.5.

Encircling prey: the location of prey is determined and circled them. In this phase, the current best position is assumed as the best candidate solution and the rest of search agent try to update their position toward the best search agents. Furthermore, the process can be expressed by the following equations.

$$\vec{D} = \left|\vec{C} \cdot \vec{X^*}(t) - \vec{X}(t)\right| \tag{3.41}$$

$$\vec{X}(t+1) = \vec{X^*}(t) - \vec{A} \cdot \vec{D} \tag{3.42}$$

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a} \tag{3.45}$$

where,

t is the current iteration,

$\vec{A}, \vec{C}$ are the coefficient vectors,

$\vec{X^*}$ is the best solution obtained so far,

X is the vector position,

$\vec{a}$ is the linearly decrease from 2 to 0,

$\vec{r}$ is the random vector from 0 to 1, and

$\vec{D}$ refers to the distance between whale and preys which is the best position obtained.

Bubble-net hunting method (exploitation phase): there are two approaches to form the mathematical problem of bubble hunting method.

- Shrinking encircling prey: the process is contributed, so it means that $\vec{A}$ is decreased when $\vec{a}$ decreases linearly. Thus, $\vec{A}$ is the random value in the interval [-a, a] that a decrease from 2 to 0. The new position of a search agent can be obtained from the original position of the agent and position of current best agent.
- Spiral updating position: the helix-shape movement of humpback whales can be formed as the spiral equation as below. It is created between the position of whale and preys.

$$\vec{X}(t+1) = \vec{D'} \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X^*}(t) \tag{3.46}$$

$$\vec{D'} = \left| \vec{X^*}(t) - \vec{X^*}(t) \right| \tag{3.47}$$

where,

b is the constant, and

l is the random number from -1 to 1.

During preys hunting, humpback whale swims around within shrinking circle and along spiral shape path simultaneously. During optimization, only 50% of assumption is chosen between either shrinking encircling or spiral shape to update the position of a whale. Moreover, it can be modelled as two equation system below.

$$\vec{X}(t+1)=\begin{cases}\vec{X^*}(t)-\vec{A}\cdot\vec{D} & if \quad p<0.5\\ \vec{D'}\cdot e^{lb}\cdot\cos(2\pi l)+\vec{X^*}(t) & if \quad p\geq 0.5\end{cases}, \tag{3.48}$$

where,

p is the random number from 0 to 1.

Search for prey (exploration phase): In this phase, the vector $\vec{A}$ is used to search randomly for preys. It means that it upgrade the position based on chosen search agents instead of best search agents to get the optimum point. Furthermore, this can be expressed in mathematical forms as the following:

$$\vec{D}=\left|\vec{C}\cdot\vec{X}_{random}-\vec{X}\right|, \tag{3.49}$$

$$\vec{X}(t+1)=\vec{X}_{random}-\vec{A}\vec{D}. \tag{3.50}$$

where,

$\vec{X}_{random}$ is the random position vector or random whale chose from the current population.

3.4 Simulation Procedure

The application of the applied algorithms in multi objective function for the active power loss minimization using GA, ABC, PSO, and WOA can be described as the following steps. Moreover, the working process of the applied algorithm is also addressed.

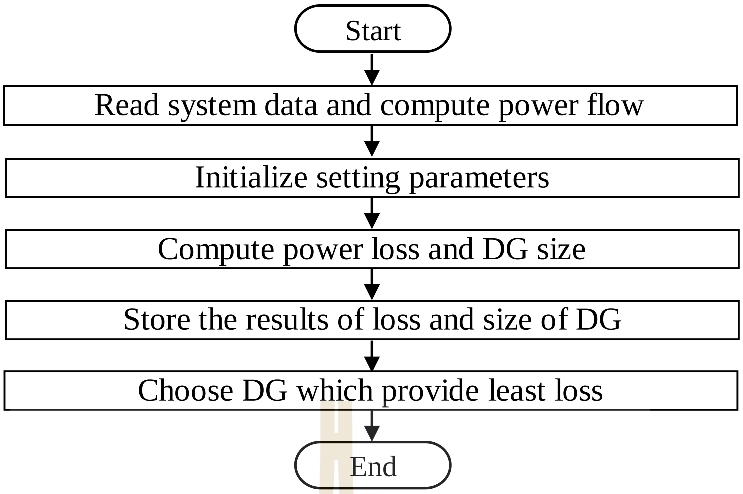

Figure 3.6 Flowchart of the proposed algorithm.

1. Read line and bus data of the system and solve feeder line flow using Newton-Raphson power flow method.
2. Initialize the population, max iteration, and constraints of DG.
3. Compute power loss and size of DG.
4. Store the obtained results of power loss and size of DG.
5. Select the DG which provides the least loss.
6. The algorithm is ended.

3.5 Chapter summary

This chaper presented the basic power flow equations, and the mathematical formulation of loss calculation was also given. Moreover, four artifical intelligence techniques such as GA, ABC, PSO, and WOA which applied to solve the problems were decribed and discussed as well as their working procedures.

CHAPTER IV

SIMULATION RESULT AND DISCUSSION

4.1 Introduction

This chapter presents the obtained results of optimal placement and size of DG in radial distribution network using the four algorithms (GA, ABC, PSO, and WOA), and the proposed algorithms were implemented and programmed in MATLAB 2014a in computer with Intel Core i5, 2.9GHz, 4GB of RAM. The algorithm was tested with various function to verify the performance and efficiency.

Table 4.1 Parameters setting values of each method.

Parameters	**Algorithms**			
	GA	ABC	PSO	WOA
Population	50	50	50	50
Maximum iteration	200	200	200	200
Maximum error	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}

The algorithms were evaluated in the application of DG with 15, 33, 69, and 85 bus test system. The AIs are used to determine both location and size of DG for comparative purpose. In this study, single DG which operates in unity power factor is considered. The setting parameters of the algorithms were shown in Table 4.1. Also, all the methods were set the same values of parameters for comparing the performance to reach convergence in term iterations. The obtained results were compared with voltage sensitivity index method of (Murthy and Kumar, 2014) and proposed method of (Reddy et al., 2017) in aims of comparing the accuracy and performances of the methods.

4.2 Digsilent Power Factory Verification

To verify the accuracy and performance of the algorithm, the results of the algorithm of 15 and 33 bus system was compared with those of Digsilent power factory software. The results of Digsilent software was the same as those of the algorithm; hence, it could be concluded that the proposed algorithm was correct and acceptable. The system diagram of 15 and 33 bus test system in Digsilent were shown in Figure 4.1 and Figure 4.3 respectively. Also, the bar color represented the level of voltage in each bus. The data of the system obtained from Digsilent software of 15 and 33 bus system was shown in Figure 4.2 and Figure 4.4 respectively.

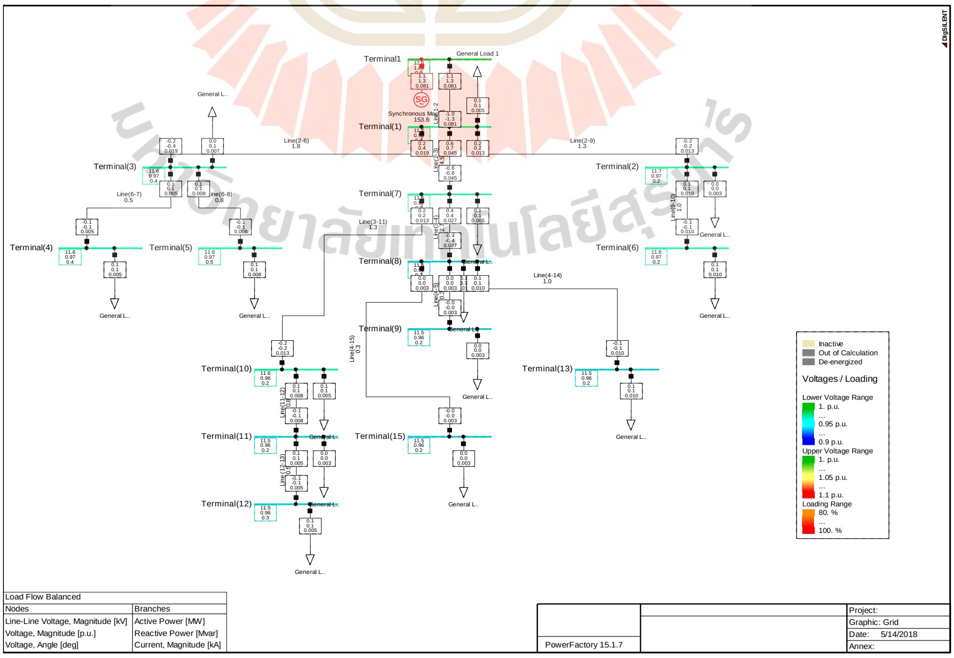

Figure 4.1 15 bus system configuration in Digsilent software.

```
                                                        DIgSILENT       Project:
                                                        PowerFactory
                                                          15.1.7        Date:  5/13/2018

Load Flow Calculation                                                          Total System Summary

    AC Load Flow, balanced, positive sequence                Automatic Model Adaptation for Convergence       No
    Automatic Tap Adjust of Transformers        No           Max. Acceptable Load Flow Error for
    Consider Reactive Power Limits              No             Nodes                                          1.00 kVA
                                                               Model Equations                                0.10 %

Total System Summary                                  Study Case: Study Case                    Annex:          / 1

No. of Substations     0         No. of Busbars      15        No. of Terminals     0        No. of Lines          14
No. of 2-w Trfs.       0         No. of 3-w Trfs.     0        No. of syn. Machines 1        No. of asyn.Machines  0
No. of Loads          14         No. of Shunts        0        No. of SVS           0

Generation           =      1.07  MW            1.31   Mvar      1.69  MVA
External Infeed      =      0.00  MW            0.00   Mvar      0.00  MVA
Load P(U)            =      1.03  MW            1.27   Mvar      1.63  MVA
Load P(Un)           =      1.03  MW            1.27   Mvar      1.63  MVA
Load P(Un-U)         =      0.00  MW            0.00   Mvar
Motor Load           =      0.00  MW            0.00   Mvar      0.00  MVA
Grid Losses          =      0.04  MW            0.04   Mvar
Line Charging        =                          0.00   Mvar
Compensation ind.    =                          0.00   Mvar
Compensation cap.    =                          0.00   Mvar

Installed Capacity   =      2.00  MW
Spinning Reserve     =      0.93  MW

Total Power Factor:
  Generation         =        0.64  [-]
  Load/Motor         =   0.63 / 0.00  [-]
```

Figure 4.2 Simulation result of 15 bus system in Digsilent.

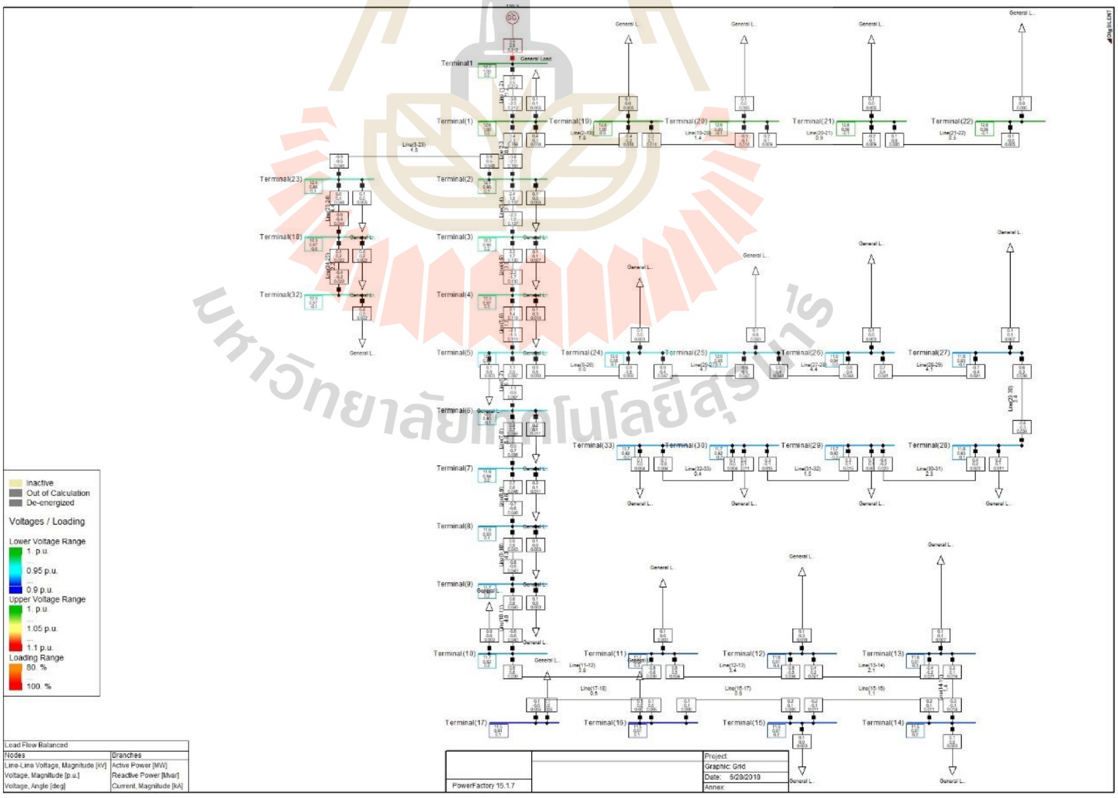

Figure 4.3 33 bus system configuration in Digsilent software.

```
--------------------------------------------------------------------------------------------------------------
|                  |                                                      |  DIgSILENT   | Project:           |
|                  |                                                      | PowerFactory |--------------------|
|                  |                                                      |    15.1.7    | Date:  6/28/2018   |
--------------------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                 Total System Summary |
--------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence           |  Automatic Model Adaptation for Convergence   No  |
|    Automatic Tap Adjust of Transformers         No     |  Max. Acceptable Load Flow Error for              |
|    Consider Reactive Power Limits               No     |     Nodes                                1.00 kVA |
|                                                        |     Model Equations                      0.10 %   |
--------------------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------------------
| Total System Summary                          | Study Case: Study Case            | Annex:           / 1 |
--------------------------------------------------------------------------------------------------------------
|                                                                                                            |
| No. of Substations    0      No. of Busbars      33      No. of Terminals     0     No. of Lines        32 |
| No. of 2-w Trfs.      0      No. of 3-w Trfs.     0      No. of syn. Machines 1     No. of asyn.Machines 0 |
| No. of Loads         32      No. of Shunts        0      No. of SVS           0                            |
|                                                                                                            |
| Generation         =      3.91  MW        2.52  Mvar      4.65  MVA        |                               |
| External Infeed    =      0.00  MW        0.00  Mvar      0.00  MVA                                        |
| Load P(U)          =      3.71  MW        2.38  Mvar      4.41  MVA                                        |
| Load P(Un)         =      3.71  MW        2.39  Mvar      4.41  MVA                                        |
| Load P(Un-U)       =      0.00  MW        0.00  Mvar                                                       |
| Motor Load         =      0.00  MW        0.00  Mvar      0.00  MVA                                        |
| Grid Losses        =      0.20  MW        0.13  Mvar                                                       |
| Line Charging      =                      0.00  Mvar                                                       |
| Compensation ind.  =                      0.00  Mvar                                                       |
| Compensation cap.  =                      0.00  Mvar                                                       |
|                                                                                                            |
| Installed Capacity =      4.00  MW                                                                         |
| Spinning Reserve   =      0.09  MW                                                                         |
|                                                                                                            |
| Total Power Factor:                                                                                        |
|   Generation       =        0.84  [-]                                                                      |
|   Load/Motor       =  0.84 / 0.00  [-]                                                                     |
|------------------------------------------------------------------------------------------------------------|
```

Figure 4.4 Simulation result of 33 bus system in Digsilent.

Table 4.2 System loss comparison of 15 and 33 bus system with Digsilent software.

	System loss (kW)	
	DigSilent	Proposed
15 bus system	40	43.20
33 bus system	200	206.5

Table 4.2 shows the comparison of simulation results of power flow in the 15 and 33 bus system. It was investigated that the obtained losses from Digsilent software simulation were comparable to those of the proposed method. As a result, it could be concluded that the power losses obtained from Digsilent software of the 69 and 85 bus system are comparable to the proposed method as well. From these regards, the proposed method could provide the reliable result effectively. To verify the voltage

profile in the system, Figure 4.5 and Figure 4.6 show the comparison of the voltage profile between Digsilent and proposed method of the 15 and 33 bus test system. It was shown that the voltage profile obtained from Digsilent was comparable to that of proposed method. It showed the accuracy and effectiveness of the proposed method.

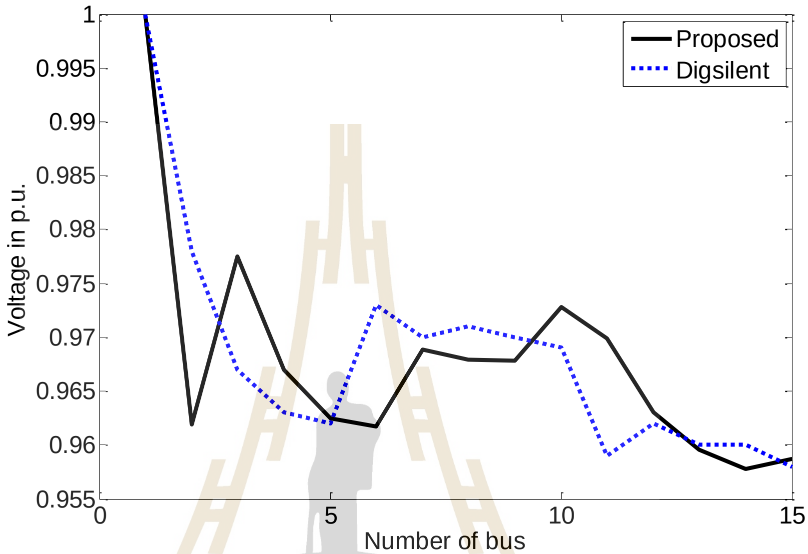

Figure 4.5 Voltage profile of Digsilent and proposed of 15 bus system.

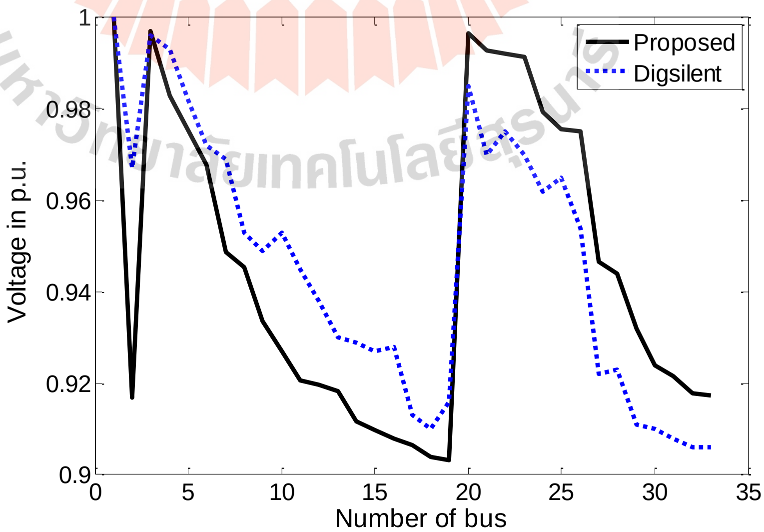

Figure 4.6 Voltage profile of Digsilent and proposed of 33 bus system.

4.3 Function Testing

To test the performance and accuracy of the algorithm, some benchmark eqaution function are considered as the tested functions. In this thesis, WOA is applied to solve the problems. Before starting to solve DG application optimization, WOA is test to minimize the multi-peak funcitons which have many local extrem values. During the optimizaiton process, it is easy to become stuck in these local minima ans lead to a premature convergence. Tables illustrate the functions including unimodal, multimodal, and fixed dimention mutlimodal benchmark functions. Furthermore, it is compared with GA to prove the performance and robustness. All the tests of the functions are carried out by setting of the parameters with population size of 50 and maximum iterations of 100.

4.3.1 Unimodal Function

Two unimodal functions are chosen as the tested functions which are illustrated in Table 4.3 including the constraints of variables and the minimum of the functions.

Table 4.3 Unimodal benchmark test functions.

No	Function	Range	$f_{\min}$
F1	$F(x)=\sum_{i=1}^{n} x_i^2$	[-100, 100]	0
F2	$F(x)=\sum_{i=1}^{n} \lvert x_i \rvert + \prod_{i=1}^{n} \lvert x_i \rvert$	[-100, 100]	0

Table 4.4 and Table 4.5 show the results of the function simulation of function F1 and function F2 which consist of fitness values solutions and average computation time after 30 trials. Comparison of WOA and GA in solving the problem is also included. Moreover, the 3D characteristic of the tested function F1 and F2 are shown in Figure 4.7 and 4.8 respectively. It is noticed that WOA provides the better results with less computation time when compared with those obtained from GA. Hence, it can be evaluated that WOA is better that GA in finding the local minimum of the functions. For tested function 1, WOA provides the average value of the fitness value of 4.91e-15 with SD of 1.14e-14 spending 0.3026s while GA gives the average value of the fitness value of 3.40e-2 with SD of 0.0855 spending 1.78s. As a result, it is proved the better accuracy of WOA over GA in finding the minimum value of the unimodal function with less CPU time as shown in Table 4.4.

Table 4.4 Statistic of fitness values and average CPU of tested function F1.

Method	Statistic fitness values				Average CPU time (s)
	Minimum	Maximum	Average	SD	
WOA	4.70E-18	1.28E-15	4.91E-15	1.14269E-14	0.3026
GA	1.03E-06	0.3981	3.40E-02	0.085563	1.7895

For the tested function F1 and F2 have an infinitely local minima. The point (0, 0, 0) is considered as the global minimum as shown in Figure 4.7 and 4.8. For tested function 2, WOA provides the average value of the fitness value of 7.21e-10 with SD of 1.39e-09 spending 0.3067s while GA gives the average value of the fitness value of 1.21e-01 with SD of 0.188 spending 2.04s. Hence, it is conveyed the better accuracy and performance of WOA over GA in finding the minimum value of the unimodal function with less CPU time as shown in Table 4.5.

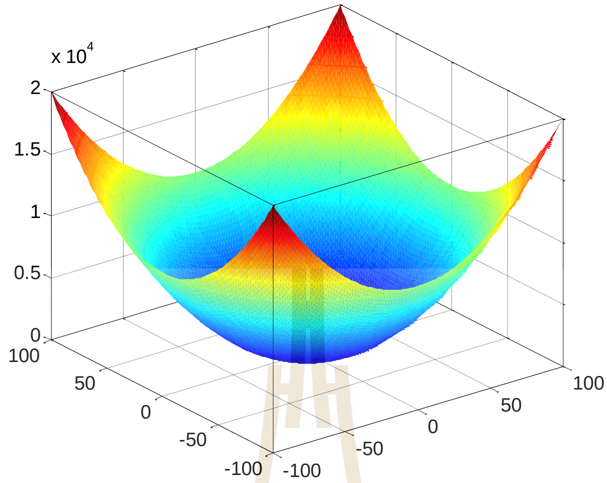

Figure 4.7 3D characteristic of tested function F1.

Table 4.5 Statistic of fitness values and average CPU of tested function F2.

Method	Statistic fitness values				Average CPU time (s)
	Minimum	Maximum	Average	SD	
WOA	1.16E-11	5.40E-09	7.21E-10	1.39978E-09	0.3067
GA	0.0068	0.6904	1.21E-01	0.188676	2.0456

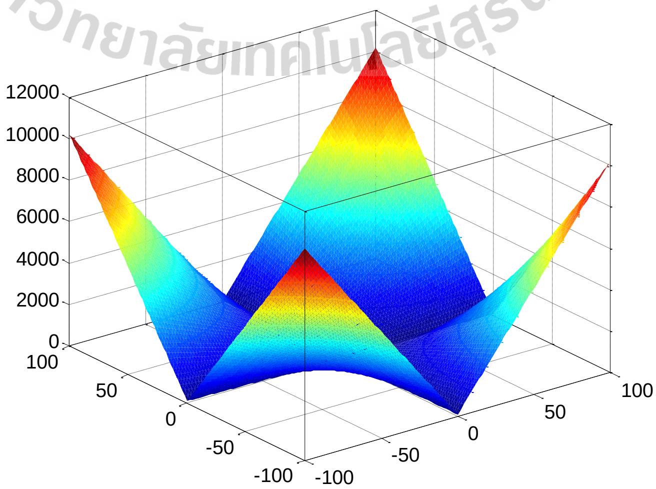

Figure 4.8 3D characteristic of tested function F2.

4.3.2 Multimodal Function

Two Multimodal functions are the tested functions which are illustrated in Table 4.6 including the constraints of variables and the minimum of the functions.

Table 4.6 Multimodal benchmark test functions.

No	Function	Range	$f_{\min}$
F3	$F(x)=\sum_{i=1}^{n}\left\|x_i^2-10\cos(2\pi x_i)+10\right\|$	[-5.12, 5.12]	0
F4	$F(x)=\frac{1}{4000}\sum_{i=1}^{n}x_i^2-\prod_{i=1}^{n}\cos\left(\frac{x_i}{\sqrt{i}}\right)+1$	[-600, 600]	0

Table 4.7 and Table 4.8 show the results of the function simulation of function F3 and function F4 which consist of fitness values solutions and average computation time after 30 trials. Comparison of WOA and GA in solving the problem is also included.

Table 4.7 Statistic of fitness values and average CPU of tested function F3.

Method	Statistic fitness values				Average CPU time (s)
	Minimum	Maximum	Average	SD	
WOA	0	5.68E-14	1.74E-09	7.43623E-09	0.4112
GA	0.0138	2.8029	7.05E-01	0.995676	1.7896

Moreover, the 3D characteristic of the tested function F3 and F4 are shown in Figure 4.9 and 4.10 respectively. It is noticed that WOA provides the better results with less computation time when compared with those obtained from GA. Hence, it can be evaluated that WOA is better that GA in finding the local minimum of the functions.

From the function tested 3, Table 4.7 shows that WOA provides the average value of the fitness value of 1.74e-09 with SD of 7.43e-09 spending 0.4112s while GA gives the average value of the fitness value of 7.05e-01 with SD of 0.995 spending 1.789s. From the results obtained, result from WOA is zero while result of GA is greater than that of GA. The minimum result of GA is 0.013. Hence, it is conveyed the better accuracy and performance of WOA over GA in finding the minimum value of the multimodal function with less CPU time.

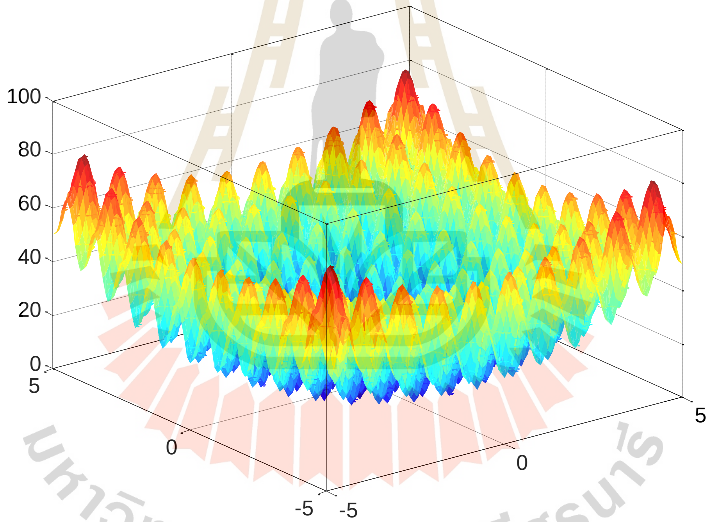

Figure 4.9 3D characteristic of tested function F3.

Table 4.8 Statistic of fitness values and average CPU of tested function F4.

Method	Statistic fitness values				Average CPU time (s)
	Minimum	Maximum	Average	SD	
WOA	2.22E-16	8.68E-14	2.21E-14	4.41312E-14	0.4038
GA	7.61E-02	1.7551	5.31E-01	0.746817	1.7660

Table 4.8 shows the obtained results of the tested function 4 of WOA and GA. From the results, WOA gives 8.68e-14, 2.22e-16, 2.21e-14, and 4.41e-14, while GA provides 1.755, 7.61e-02, 5.31e-01, and 0.746 for the maximum, minimum, average, and SD of the fitness values respectively. Moreover, the CPU time of WOA and GA are 0.403s and 1.766s respectively. It is observed that result from WOA is closer to zero which is the best answer. Hence, it can be concluded that WOA provides better solutions than GA in finding the fitness value of multimodal function with less CPU time to reach the convergence.

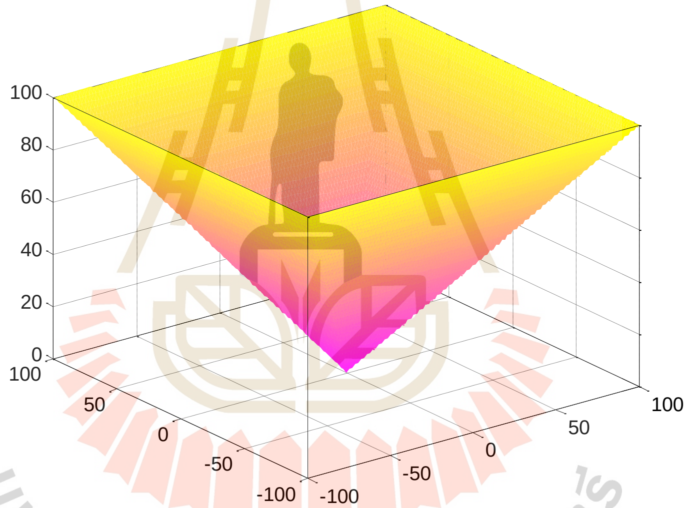

Figure 4.10 3D characteristic of tested function F4.

4.3.3 Fixed-dimension multimodal Function

Two fixed-dimension multimodal functions are illustrated in Table 4.9 including the constraints of variables and the minimum of the functions. Table 4.10 and Table 4.11 show the results of the function simulation of function F5 and function F6 which consist of fitness values solutions and average computation time after 30 trials. Comparison of WOA and GA in solving the problem is also included. Moreover, the

3D characteristic of the tested function F3 and F4 are shown in Figure 4.11 and 4.12 respectively. It is noticed that WOA provides the better results with less computation time when compared with those obtained from GA. Hence, it can be evaluated that WOA is better that GA in finding the local minimum of the functions.

Table 4.9 Fixed-dimension multimodal benchmark test functions.

No	Function	Range	$f_{\min}$
F5	$F(x)=\left(\frac{1}{500}+\sum_{j=1}^{25}\frac{1}{j+\sum_{i=1}^{2}(x_i-a_{ij})^6}\right)^{-1}$	[-65, 65]	1
F6	$F(x)=\left(x_2-\frac{5.1}{4\pi^2}x_1^2+\frac{5}{\pi}x_1-6\right)^2+10\left(1-\frac{1}{8\pi}\right)\cos x_1+10$	[-5, 5]	0.398

Table 4.10 Statistic of fitness values and average CPU of tested function F5.

Method	Statistic fitness values				Average CPU time (s)
	Minimum	Maximum	Average	SD	
WOA	0.9980	2.0039	1.210	1.253893	0.4149
GA	0.9980	3.9700	1.740	1.995730	2.4991

Table 4.10 shows the obtained results of the tested function 5 of WOA and GA. From the results, WOA gives 2.00, 0.998, 1.210, and 1.253, while GA provides 3.970, 0.998, 1.740, and 1.995 for the maximum, minimum, average, and SD of the fitness values respectively. Moreover, the CPU time of WOA and GA are 0.414s and 2.499s respectively. It is observed that result from WOA is closer to the best answer as shown in Table 4.10. Hence, it can be concluded that WOA provides better solutions

than GA in finding the fitness value of multimodal function with less CPU time to reach the convergence.

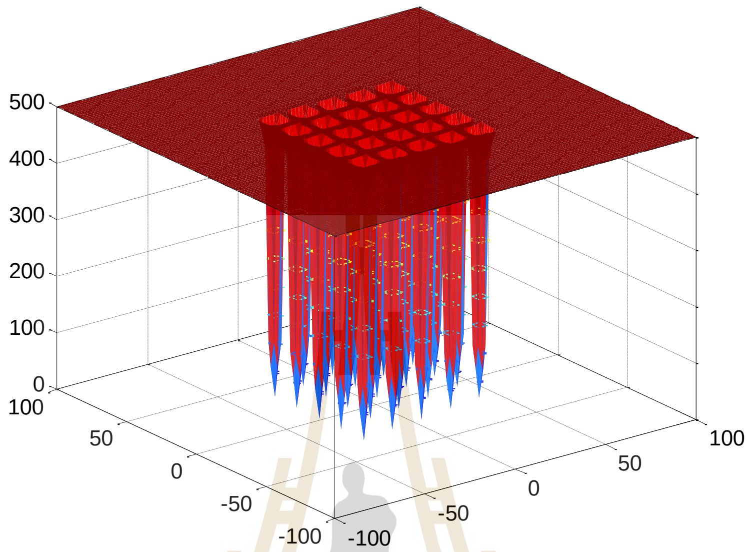

Figure 4.11 3D characteristic of tested function F5.

Table 4.11 Statistic of fitness values and average CPU of tested function F6.

Method	Statistic fitness values				Average CPU time (s)
	Minimum	Maximum	Average	SD	
WOA	0.39789	0.40006	0.3980	0.38807	0.680
GA	0.398	0.4329	0.4000	0.38871	1.4751

Table 4.11 shows the obtained results of the tested function 6 of WOA and GA. From the results, WOA gives 0.400, 0.397, 0.398, and 0.388, while GA provides 0.432, 0.398, 0.400, and 0.388 for the maximum, minimum, average, and SD of the fitness values respectively. Moreover, the CPU time of WOA and GA are 0.680s and 2.499s respectively. It is observed that result from WOA is closer to 0.1.475 which

is the best answer. Hence, it can be concluded that WOA provides better solutions than GA in finding the fitness value of multimodal function with less CPU time to reach the convergence.

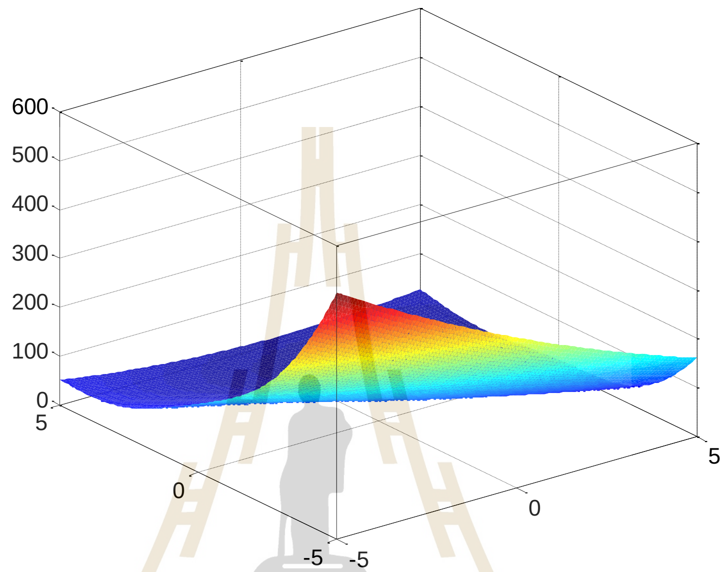

Figure 4.12 3D characteristic of tested function F6.

4.4 15 Bus Test System

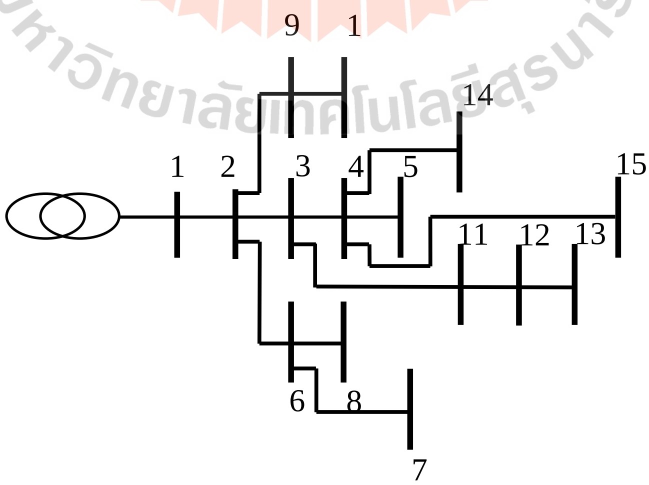

Figure 4.13 15 buses of the radial distribution network.

15 buses of the radial distribution system which was tested with the proposed algorithm as shown in Figure 4.13. The bus data and line data can be obtained from (Das et al., 1995). Bus 1 is considered as the reference bus and bus 2 to 15 are the load buses. The system power loss before minimization was 43.2kW which were obtained using Newton-Raphson method.

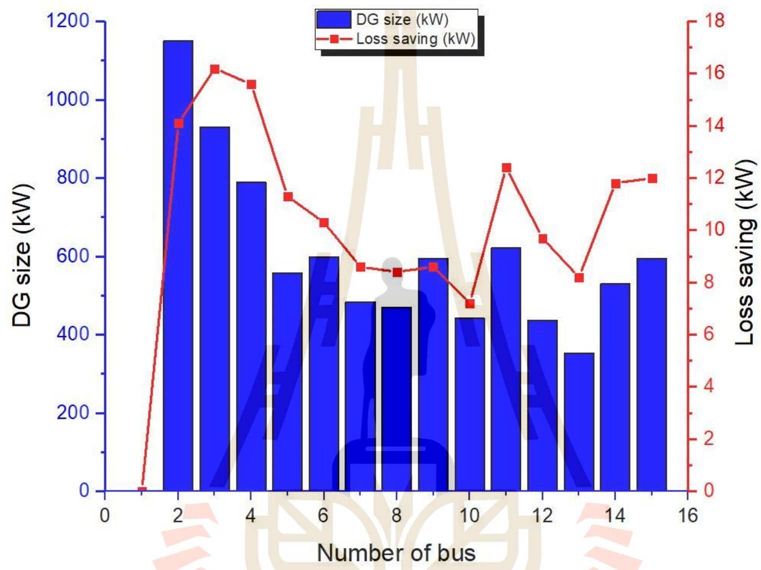

Figure 4.14 Loss saving and DG's size of 15 bus system**.**

Figure 4.14 showed the loss saving in each bus corresponding to the size DG. It was observed that loss savings were varied by the location and size of DG in the system. Furthermore, DGs placed in non-optimal bus caused to less saving with high capacity of DG. DG at bus 2 and bus 9 provided less loss saving with the high size of DG because they were placed at the first and end bus of the system, for instance. The optimal location of DG in this system was bus 3 which gave highest loss saving. Table 4.12 shows the optimum results of location, size, and power loss after placing the DG in the system. The optimum location obtained from the algorithms was bus 3. All the four algorithms provided the comparable loss saving and location with a different capacity of DG. The obtained sizes of DG from GA, ABC, PSO, and WOA were 928.60kW, 931.54kW, 931.20kW, and 932.96kW respectively. Moreover, it was noticed that WOA provided the least loss DG when compared to other three methods. The loss obtained from WOA was 26.97kW while GA, ABC, and PSO provided 27.30kW, 27.0kW, and 27.10kW respectively.

Table 4.12 Results of 15 bus system**.**

Parameters	Without DG	With DG			
		GA	ABC	PSO	WOA
Loss (kW)	43.2	27.30	27.0	27.10	26.97
Location	-	3	3	3	3
Size (kW)	-	928.60	931.54	931.20	932.96
Loss saving (kW)	-	15.90	16.20	16.10	16.23
Loss reduction (%)	-	36.80	37.50	37.26	37.56
CPU time (s)	-	24.13	150.67	217.32	23.64

The CPU time of GA, ABC, PSO, and WOA were 24.13s, 150.67s, 217.32s, and 23.63s respectively. It was noticed that WOA spent less time to reach the solution followed by GA, ABC, and PSO. WOA spent only 23.64s while GA spent 24.13s. Moreover, PSO spent more time to reach convergence. The voltage profile of before and after installing DG in the system was compared as shown in Figure 4.15. It was investigated that the voltage profile in the base case was poor because it was closed to the lower boundary of the specified range, but it was improved significantly after placing the DG with optimal bus and size. The voltage of buses at the end of the system was dropped a little bit before having DG. However, it was enhanced to the better range. In this test system, it was concluded that WOA gave the better results when compared to GA, ABC, and PSO with less computation time.

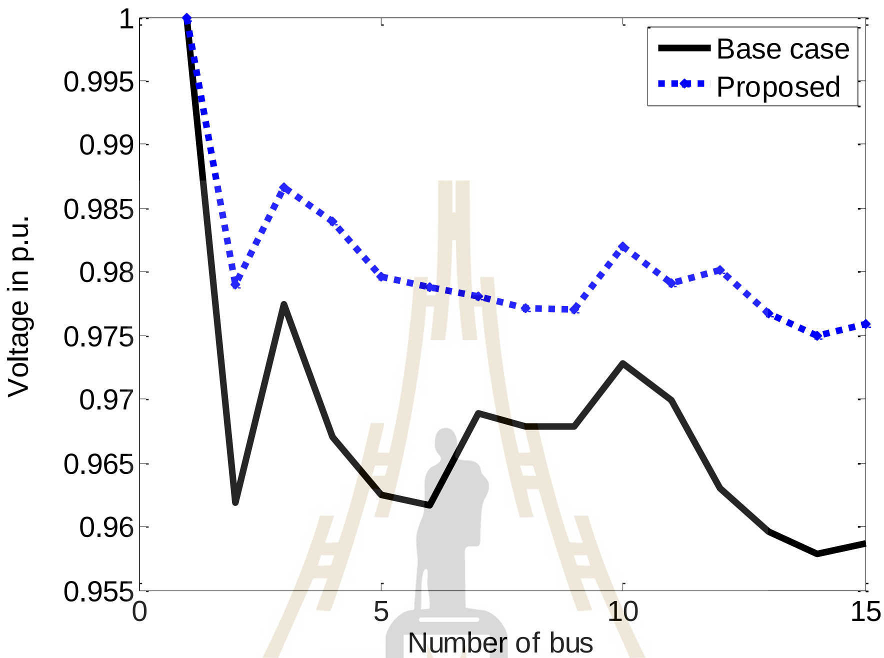

Figure 4.15 Voltage profile comparison of 15 bus system.

Table 4.13 Comparison of results of 15 bus system.

Parameters	Voltage sensitivity index (Murthy, 2013)	Reddy et al., (2017)	Proposed
Location	-	6	3
Size (kW)	-	598.4	932.96
Loss (kW)	-	32.9	26.97
Saving (kW)	-	10.3	16.23

Table 4.13 showed the comparison of the obtained solution of the proposed method and Reddy et al., (2017). Reddy et al., used voltage vector index to determine

the location of DG and applied WOA to find the size of DG. The obtained size of DG of the proposed method and Reddy et al., (2017) were 598.4kW and 932.96kW respectively. It was shown that the proposed method provided 16.23kW while Reddy et al., gave 10.3kW of loss saving. It could be assumed that the proposed method provided a better solution in optimal DG application. The convergence characteristic comparison of the methods was shown in Figure 4.16. It showed that better performance of WOA over other three algorithm in reaching global solution with the same setting parameters.

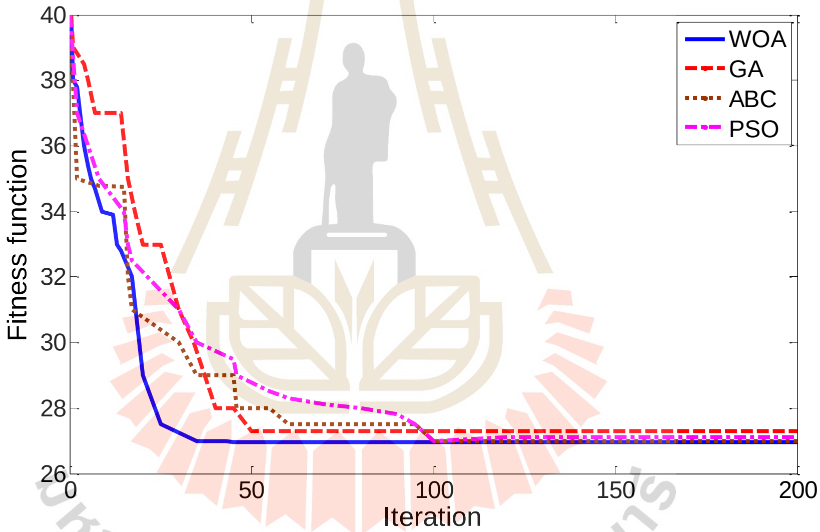

Figure 4.16 Convergence characteristic comparison of 15 bus system.

4.5 33 Bus Test System

The 33 buses of the radial distribution system are shown in Figure 4.17. It consists of totally 33 buses and 32 lines or branches. The whole system is conneted to a power transformer at 12.66kV of the secondary side while it is loaded totally of 3.715MW and 2.3MVar. Bus 1 is considered as the reference bus and others are load buses. The system data can be obtained in (Prakash and Khatod, 2016). The system power loss before the simulation was 206.5kW.

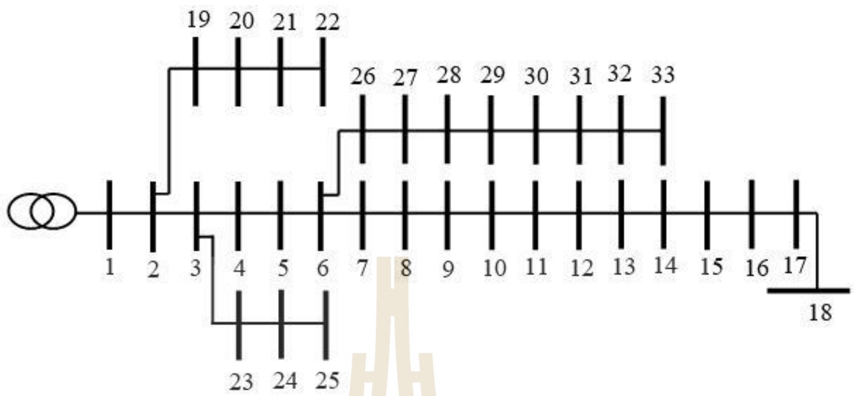

Figure 4.17 33 buses of the radial distribution network.

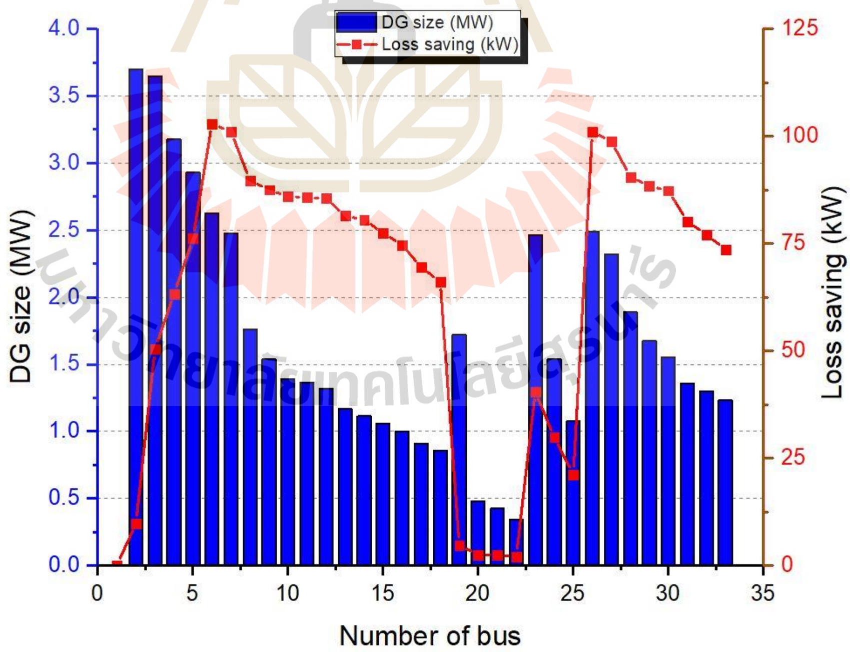

Figure 4.18 Loss savings and DG's sizes of 33 bus system.

Table 4.14 Results of 33 bus system**.**

Parameters	Without DG	With DG			
		GA	ABC	PSO	WOA
Loss (kW)	206.5	103.68	103.65	103.62	103.62
Location	-	6	6	6	6
Size (MW)	-	2.615	2.625	2.626	2.626
Loss saving (kW)	-	102.9	102.9	102.9	102.9
Loss reduction (%)	-	49.83	49.83	49.83	49.83
CPU time	-	73.72	596.95	829.70	60.20

Loss saving with a capacity of DG when it was placed in each bus was illustrated in Figure 4.18. From the figure, it was observed that the highest loss saving could be achieved when placed DG at bus 6 with a capacity of 2.626MW followed by bus 25 which provide loss saving of 102kW with a capacity of 2.5MW. Moreover, it was also investigated that when DG was placed at the non-optimal location, it gave very less loss saving with high capacity of DG size. For instance, when DG was placed at bus 1, bus 2, bus 3, the sizes of DG were high with less loss saving. Table 4.14 showed the results of the four methods, and each method provided the comparable loss saving with the comparable size of DG. The obtained sizes of DG were 2.629MW, 2.627MW, 2.627MW, and 2.626MW of GA, ABC, PSO, and WOA respectively. It was noticed that obtained size of DG from WOA was lower when compared with that of other three methods. In term of CPU time, WOA spent less time to reach the solution with 60.20s while GA, ABC, and PSO spent 73.72s, 596.95s, and 829.90s respectively. PSO spent more time followed by ABC, and GA.

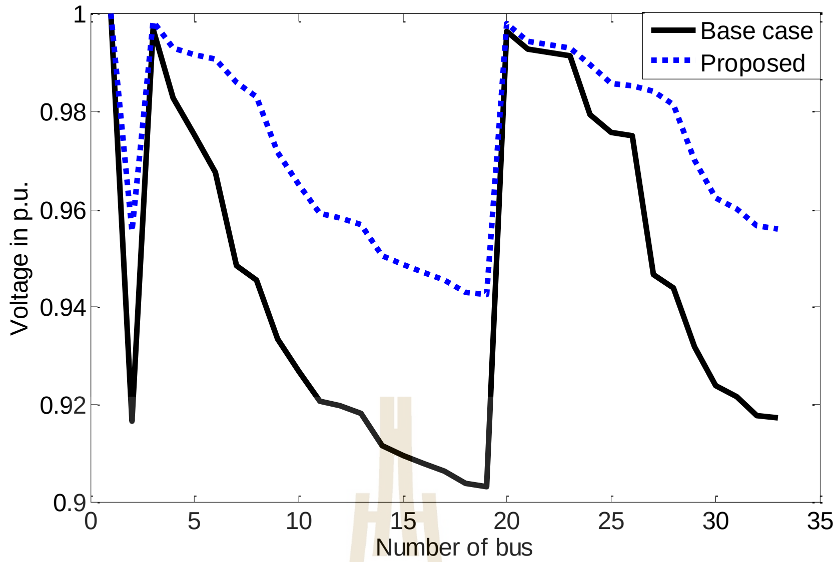

Figure 4.19 Voltage profile comparison of 33 bus system.

Before placing DG, the voltage profile was poor since most of the bus voltage was closed to the lower boundary of the specified range. Nonetheless, it was improved significantly after adjusting DG size to its optimum point as illustrated in Figure 4.19. Moreover, the convergence characteristic of the four algorithm was illustrated in Figure 4.20. It proved that WOA could reach the solution with less CPU time.

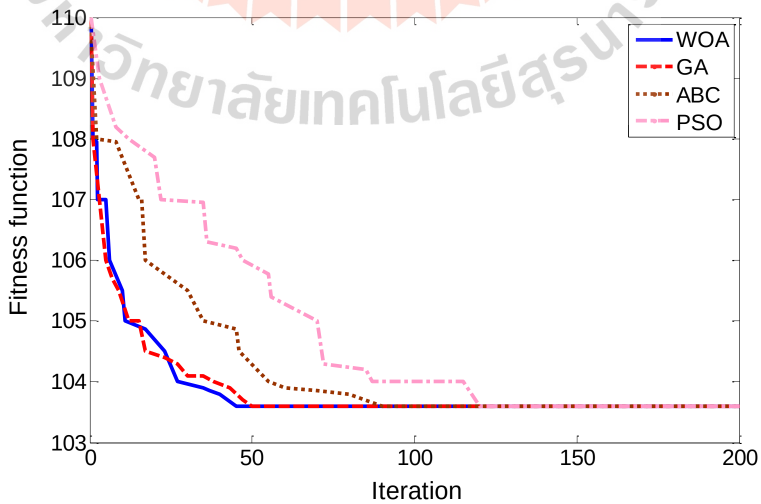

Figure 4.20 Convergence characteristic comparison of 33 bus system.

The results of the proposed method were compared with other two methods as shown in Table 4.15. Murthy (2013) used voltage sensitivity index to determine the placement of DG and varied size of DG. The location of this method was bus 16 while Reddy et al., found that bus 15 was the most suitable location for DG installation. The sizes of DG of voltage sensitivity index of (Murthy, 2013), (Reddy et al., 2017) and the proposed method were 1MW, 1.060MW, and 2.626MW with the losses of 131.9kW, 129kW, and 103.6kW respectively. Hence, the proposed method provided better results when compared with those of the other two methods. From the result, it was shown that WOA gave the better solutions when compared to the two methods in term loss reduction.

Table 4.15 Comparison of the result of 33 bus system.

Parameters	Voltage sensitivity index (Murthy, 2013)	Reddy et al., (2017)	Proposed
Location	16	15	6
Size (MW)	1	1.060	2.626
Loss (kW)	131.9	129	103.6
Saving (kW)	74.6	77.5	102.9

4.6 69 Bus Test system

The 69 buses of the radial distribution system were shown in Figure 4.13. It consists of totally 69 buses and 68 lines or branches. The whole system is conneted to a power transformer at 12kV of the secondary side. Bus 1 is considered as the reference bus and the ramainings are load buses. The system data can be obtained in (Baran and Wu, 1989). The system power loss before the simulation was 245.88kW.

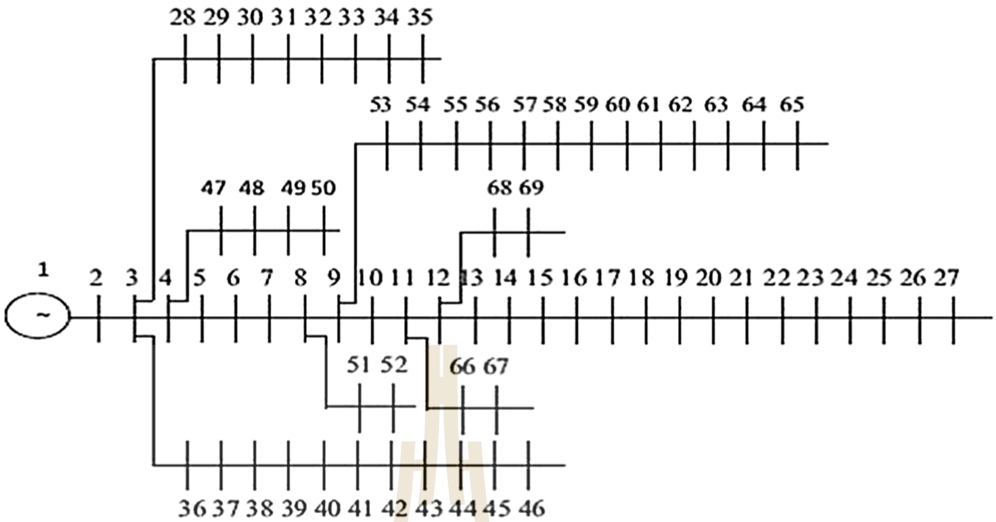

Figure 4.21 69 buses of the radial distribution network (Reddy et al., 2017).

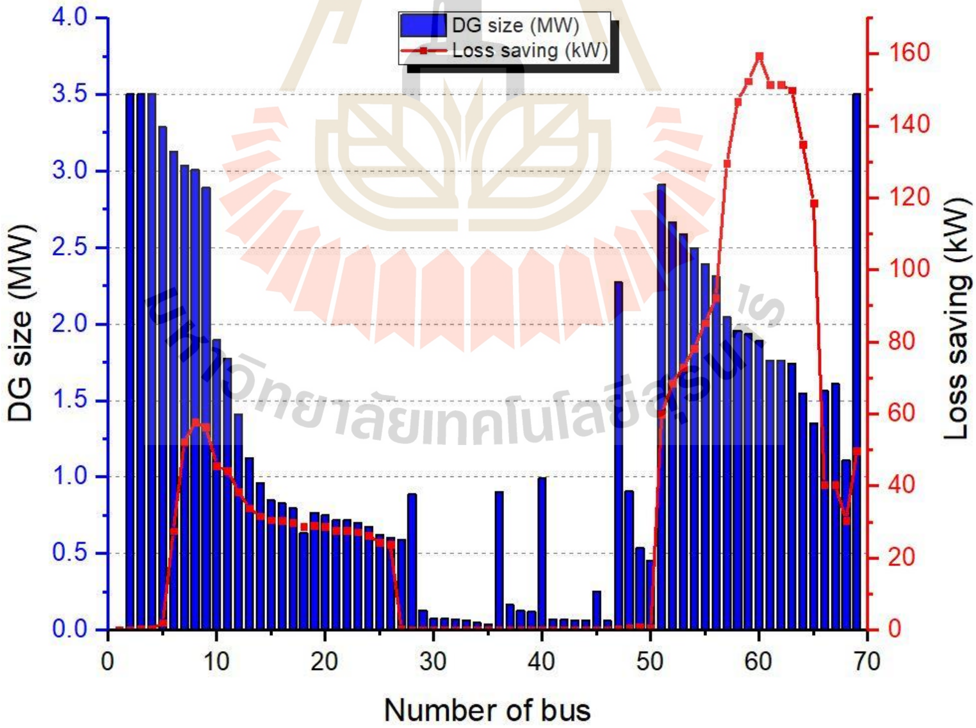

Figure 4.22 Loss savings and DG's sizes of 69 bus system.

Table 4.16 Results of 69 bus system.

Parameters	Without DG	With DG			
		GA	ABC	PSO	WOA
Loss (kW)	245.88	86.47	86.43	86.45	86.41
Location	-	60	60	60	60
Size (MW)	-	1.878	1.888	1.882	1.889
Loss saving (kW)	-	159.48	159.48	159.48	159.48
Loss reduction (%)	-	64.86	64.86	64.86	64.86
CPU time (s)		464.23	2626.48	3251.79	442.34

Loss saving with a capacity of DG when it was placed in each bus was illustrated in Figure 4.22. From the figure, it was observed that the highest loss saving could be achieved when placed DG at bus 60 with a capacity of 1.887MW followed by bus 59 which provide loss saving of 152.48kW with a capacity of 1.9325MW. Moreover, it was also investigated that when DG was placed at the non-optimal location, it gave very less loss saving with high capacity of DG size. For instance, when DG was placed at bus 1 to bus 10, the sizes of DG were high with less loss saving due to far distance of generation from the loads. Table 4.16 showed the results of the four methods, and each method provided the same loss saving with the comparable size of DG. The obtained sizes of DG were 1.878MW, 1.888MW, 1.882MW, and 1.889MW of GA, ABC, PSO, and WOA respectively, and the power loss obtained of GA, ABC, PSO, and WOA were 86.47kW, 86.43kW, 86.45kW, and 86.41kW. It was noticed that obtained loss of DG from WOA was lower when compared with that of other three methods. The loss and size obtained from the methods were comparable, but the better results were achieved with WOA.

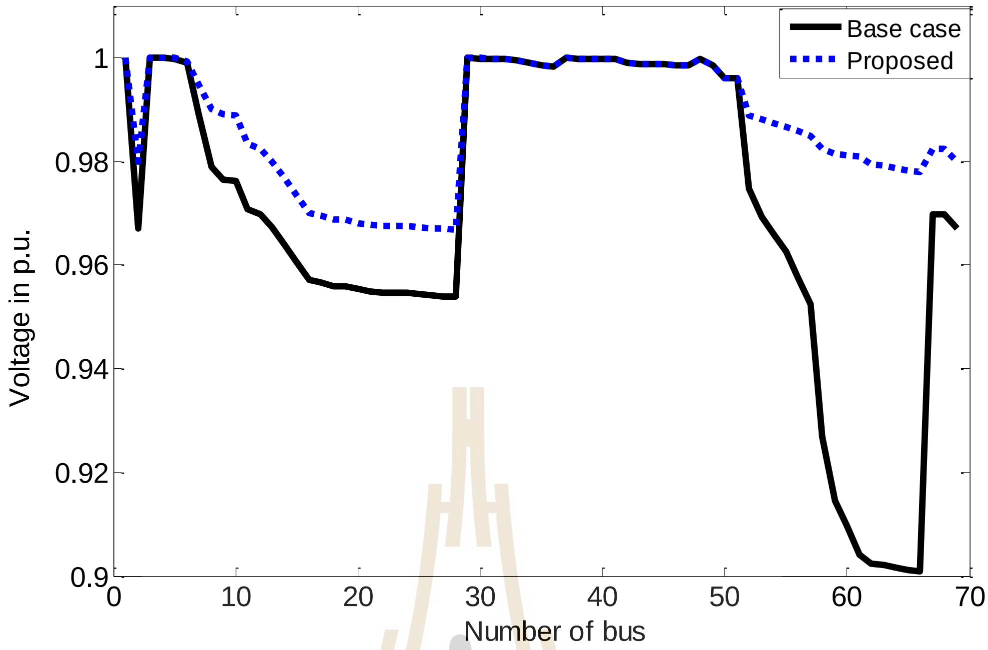

Figure 4.23 Voltage profile comparison of 69 bus system.

In term of convergence reaching, WOA spent only 432.34s to reach the solution while GA, ABC, and PSO spent 464.23s, 2626.48s, and 3251.79s respectively. The voltage profile of before and after installing DG in the system was compared as shown in Figure 4.23. It was investigated that the voltage profile in the base case was poor because it was closed to the lower boundary of the specified range especially the buses which were located at the end of the system, but it was improved significantly after placing the DG at the optimal bus and size. The voltage of buses at the end of the system was dropped a bit before having DG, and it was improved significantly after installing DG. The convergence characteristic comparison of each algorithm was shown in Figure 4.24 and it showed the better convergence curve obtained from WOA followed by GA, ABC, and PSO.

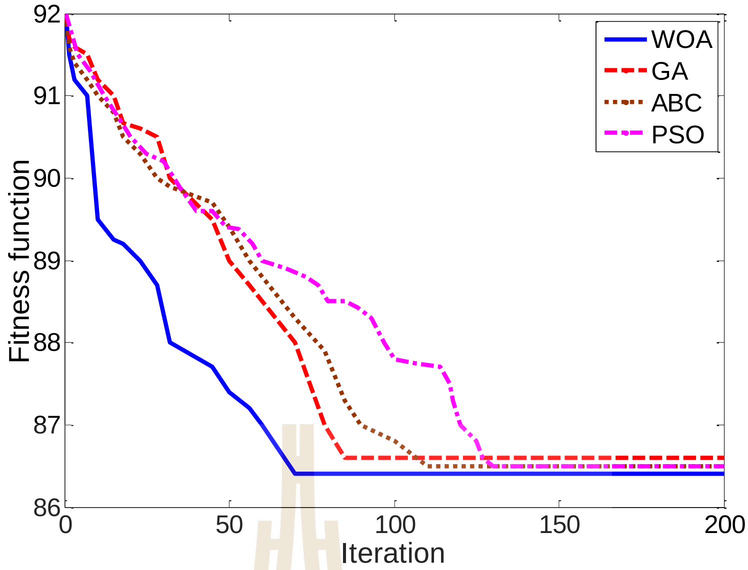

Figure 4.24 Convergence characteristic comparison of 69 bus system.

When comparing with the two methods of voltage sensitivity index of (Murthy, 2013) and (Reddy et al., 2017), it was observed that the proposed method gave the better results as shown in Table 4.17 because the loss saving obtained from the proposed method was higher than those of the other two methods. Reddy et al., found that bus 61 was the suitable location while Murthy found that bus 65 was the location for DG installation with capacity of 1.760MW and 1.352MW respectively. From the proposed method, it was found that bus 60 was the optimal location for DG placement with a size of 1.887MW. As a result, the loss obtained from the proposed method was lower.

Table 4.17 Comparison of the result of 69 bus system.

Parameters	Voltage sensitivity index (Murthy, 2013)	Reddy et al., (2017)	Proposed
Location	65	61	60
Size (MW)	1.352	1.760	1.889
Loss (kW)	127.2	94.5	86.4
Saving (kW)	118.68	151.38	159.48

4.7 85 Bus Test system

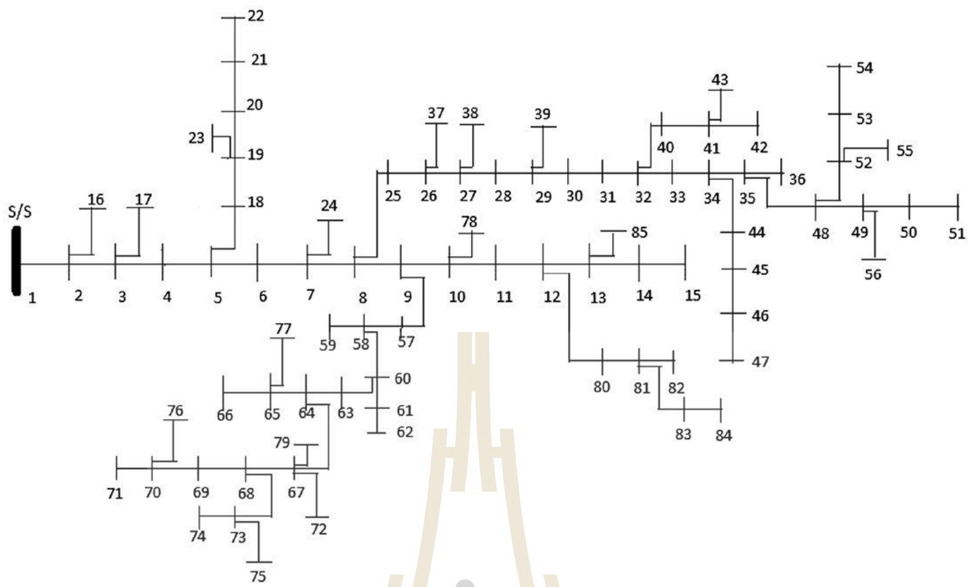

Figure 4.25 85 buses of the radial distribution network (Reddy et al., 2017).

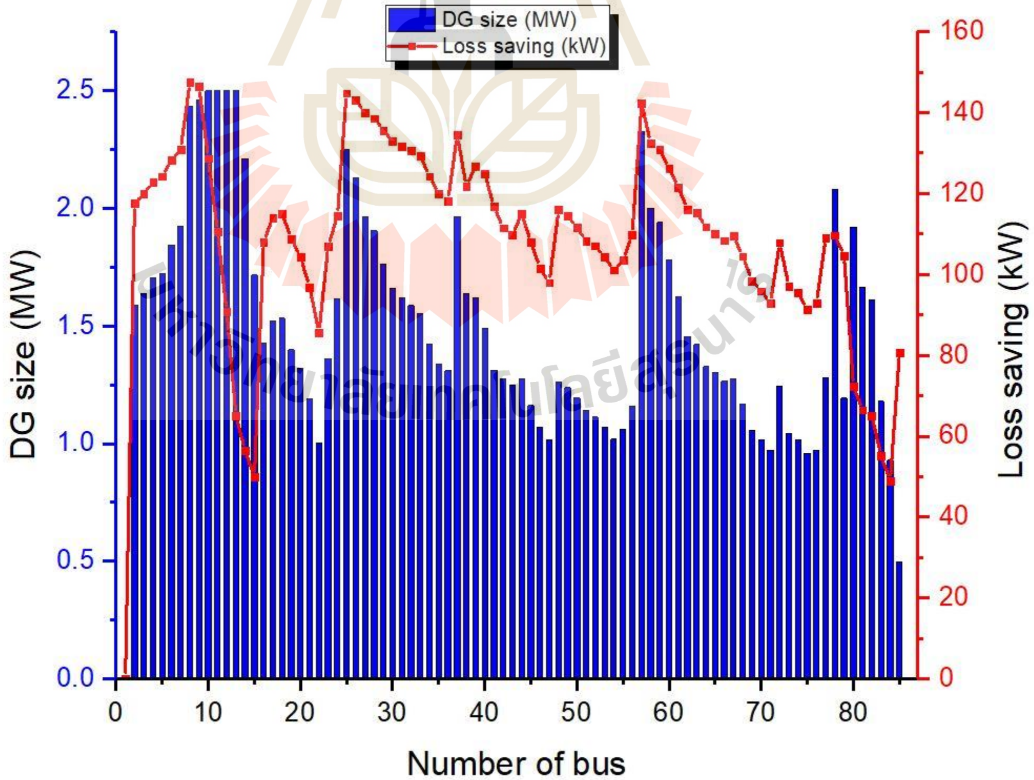

Figure 4.26 Loss savings and DG's sizes of 85 bus system.

The 85 buses of the radial distribution system were shown in Figure 4.25. It consists of totally 85 buses and 84 lines or branches. The whole system is conneted to a power transformer at 12kV of the secondary side. Bus 1 is considered as the reference bus and the remainings are load buses. The system data can be obtained in (Das et al., 1995). The system power loss before the simulation was 297.04kW.

Table 4.18 Results of 85 bus system.

Parameters	Without DG	With DG			
		GA	ABC	PSO	WOA
Loss (kW)	297.04	149.67	149.64	149.65	149.62
Location	-	8	8	8	8
Size (MW)	-	2.442	2.448	2.445	2.456
Loss saving (kW)	-	147.37	147.40	147.39	147.42
Loss reduction (%)	-	49.61	49.62	49.61	49.62
CPU time (s)		1567.56	3890.75	4586.12	1497.43

Figure 4.26 illustrated the size of DG which placed in each bus including the loss saving. The highest loss saving could be obtained by placing DG at bus 8 with a capacity of 2.456MW. Table 4.18 showed the results of the four methods, and each method provided the comparable size of DG and loss. The obtained sizes of DG were 2.442MW, 2.448MW, 2.445MW, and 2.456MW of GA, ABC, PSO, and WOA respectively. It was noticed that obtained loss of DG from WOA was lower when compared with those of other three methods. Moreover, WOA spent less time to reach the solutions when compared to other three algorithm. WOA spent only 1497.43s while GA, ABC, and PSO spent 1567.56s, 3890.75s, and 4596.12s respectively. Therefore,

it was concluded that WOA provide that better results and performance in loss minimization and fast performance.

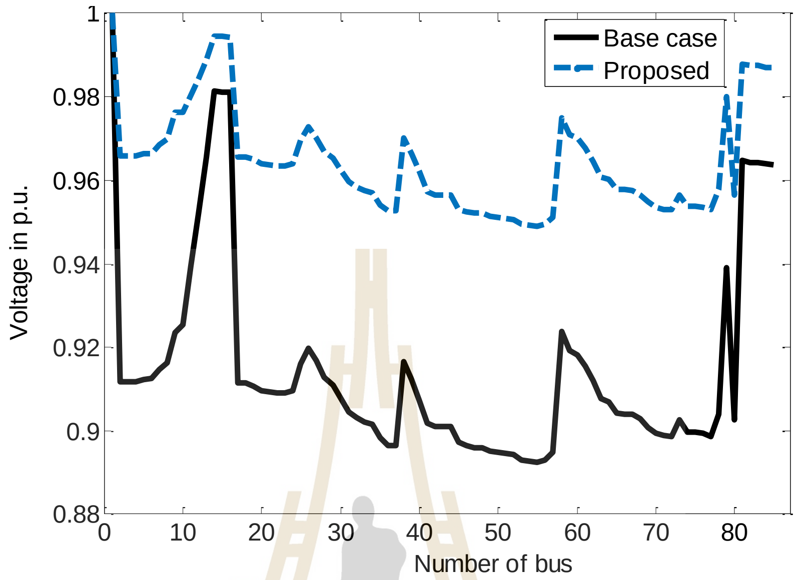

Figure 4.27 Voltage profile comparison of 85 bus system.

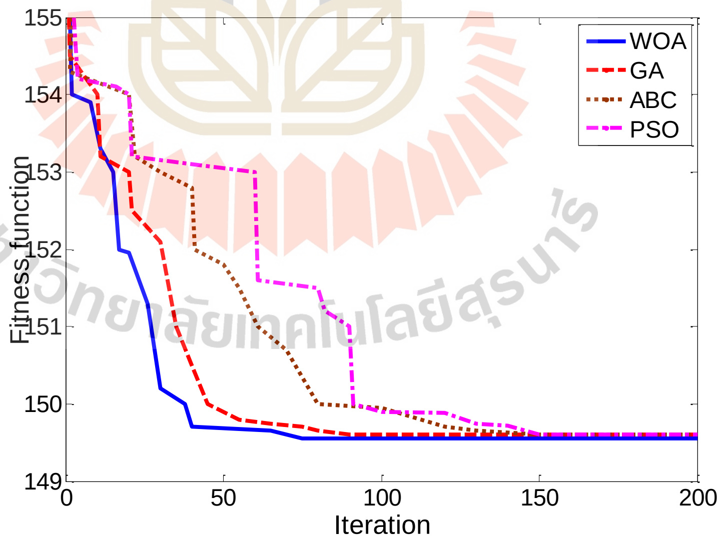

Figure 4.28 Convergence characteristic comparison of 85 bus system.

The voltage profile of before and after installing DG in the system was compared as shown in Figure 4.27. It was investigated that the voltage profile in the base case was very poor because it was lower boundary of the specified range at some buses, but it was improved significantly after placing the DG at the optimal bus and size. The voltage of buses at the end of the system was dropped a bit before having DG, and it was improved significantly after installing DG. Also, the convergence characteristic comparison of each algorithm was shown in Figure 4.28. It proved that WOA was faster to reach the solution followed by GA, ABC, and PSO.

Table 4.19 Comparison of the result of 85 bus system.

Parameters	Voltage sensitivity index (Murthy, 2013)	Reddy et al., (2017)	Proposed
Location	-	55	8
Size (MW)	-	1.061	2.456
Loss (kW)	-	193.5	149.62
Saving (kW)	-	103.54	147.42

Table 4.19 showed the comparison of the obtained results from the proposed method with voltage vector index method. Reddy et al., found that bus 55 was the suitable location for DG installation with a capacity of 1.061MW while the proposed method gave bus 8 was the optimal location. For the results, it was shown that the proposed method provide higher loss saving.

4.8 Chapter Summary

This chapter illustrates the results of the proposed methods, and four radial systems of 15, 33, 69, and 85 buses were implemented as tested cases. The DG is placed in every bus to check which bus provides the highest loss saving. Then, the most appropriate location of DG placement is found. The results are compared with four algorithms including GA, ABC, PSO, and WOA in order to verify the performance and efficiency of the proposed technique. It is investigated that WOA provides the better results when compared to those of other three algorithms. Furthermore, the obtained results are compared with results of voltage sensitivity index of (Murthy, 2013) and (Reddy et al., 2017) for comparative purpose, and it is shown that the proposed method gives the better results. The solution of power flow of the proposed method is verified with Digsilent power factory software to convey the accuracy and reliability of the method.

CHAPTER V

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

Due to the emerging of advanced technology and concern for power quality in distribution site, the installation of DG is becoming a hot topic for researchers. Meanwhile, the utility companies are starting to reconfiguration their system to integrate with DG to get high benefits. These advantages include reducing power loss, improving voltage profile, reducing emission impacts, and enhancing power quality. Nevertheless, selecting the placement and size for DG is not the easy tasks because it causes the negative impacts to the system and utilities when DG is placed in non-optimal location and size. To get high benefits, DG must be placed in an optimal location with optimal size in the distribution network.

In this thesis, the optimization algorithm techniques including GA, ABC, PSO, and WOA are used to deal with DG application in the radial distribution system for comparing the performance and effectiveness of the method. Newton-Raphson method is applied to solve power flow problem while AI techniques are used to find location and size of DG in the system. DG which operates unity power factor is considered in this work. Four radial distribution networks include 15, 33, 69, and 85 buses are implemented as tested cases. The optimal location and capacity of DG can be identified where the highest loss saving is achieved, and the four methods give the same optimum location and comparable size. Moreover, it is investigated that WOA always provides the better results when compared with those of other three methods.

To verify the performance and efficiency of the proposed method, the results are compared with those of voltage sensitivity index of (Murthy, 2013) and method of (Reddy et al., 2017). It is shown that the proposed method gives the better result in term of loss saving in the system. Digsilent power factory software is used to compare the results of power flow with the proposed method. It is illustrated that the proposed algorithm provides the reliable and correct solution.

5.2 Future Work

This proposed algorithm can apply to solve optimization for DG in all radial distribution systems. The further works will consider and analyses the other types of DGs which operate in power lagging power factor and inject both real and reactive power. Also, the characteristics of other types of DG can be presented. Cost function integrated with loss function is combined with the objective function will be included. The future research will also consider the impact of DG in relay protecting the system when integrating with DG, and setting of relaying system.

REFERENCES

Abu-Mouti, F. S. and El-Hawary, M. E., (2011), Heuristic Curve-fitted Technique for Distributed Generation Optimization in Radial Distribution Feeder Systems, **Generation, Transmission & Distribution, IET**, 5(2): 172-180.

Abu-Mouti, F. S. and El-Hawary, M. E., (2011), Optimal Distributed Generation Allocation and Sizing in Distribution Systems via Artificial Bee Colony Algorithm, **Power Delivery, IEEE Transactions**, 26(4): 2090-2111.

Acharya, N., Mahat, P., and Mithulananthan, N., (2006), An analytical approach for DG allocation in primary distribution network, **International Journal of Electrical Power & Energy Systems**, 28(10): 669-678.

Ackermann, T., Andersson, G. and Sder, L., (2001), Distributed generation: a definition, **Electric Power Systems Research**, 57: 195–204.

Al-Abri, R., (2012), Voltage Stability Analysis with High Distributed Generation (DG) Penetration, **PhD Thesis**, University of Waterloo, Waterloo, Ontario, Canada.

Alhajri, M. F. and El-Hawary, M. E., (2007), Optimal Distribution Generation Sizing via Fast Sequential Quadratic Programming. **Power Engineering, 2007 Large Engineering Systems Conference**.

Ali., E. S., Abd Elazim, S. M., and Abdelaziz, A. Y., (2017), Ant Lion Optimization Algorithm for Optimal Location and sizing of renewable distributed Generation, **Renewable Energy, Elsevier,** 101: 1311-1324.

Alinejad-Beromi, Y., Sedighizadeh, M., Bayat, M. R., and Khodayar, M. E., (2007), Using Genetic Algorithm for Distributed Generation Allocation to Reduce Losses and Improve Voltage Profile, **Universities Power Engineering Conference,** (pp. 954-959).

Alinezhad, P., Bakhoda, O.Z., and Menhaj, A.B., (2015), Optimal DG Placement and Capacity Allocation Using Intelligent Algorithms, **2015 4th Iranian Joint Congress on Fuzzy and Intelligent System (CFIS)**, 978-1-4673-8545-9/15.

Al sabounchi, A. M. M., (2011), Optimal Sizing and Location of Photovoltaic Generators on Three Phase Radial Distribution Feeder, **PhD Thesis, De Monfort University.**

Anumaka, M. C., (2012), Analysis of technical loss in electrical power system (Nigerian 330kV as a case study), **IJRRAS**.

Aref, A., Davoudi, M., Razavi, F., and Davoodi, M., (2012), Optimal DG Placement in Distribution Network Using Intelligent System, **Energy and Power Engineering**, 4: 92-98.

Baran, M.E. and Wu, F.F., (1989), Optimal Sizing of Capacitors Placed on a Radial Distribution System, **IEEE Transaction on Power System Delivery,** 29(4): 1831-1840.

Behnke, M., Erdman, W., Horgan, S., Dawson., D., Feero, W., Soudi, F., Smith, D., Whitaker, C., and Kroposki, B., (2005), Secondary Network Distribution Systems Background and Issues Related to the Interconnection of Distributed Resources, **Technical Report: NREL/TP-560-38079 by National Renewable Energy Laboratory**, USA.

Borges, C. T. L. and Falcao, D. M., (2006), Optimal Distributed Generation Allocation for Reliability, Losses and Voltage Improvement. **International journal of power and energy systems**, 28(6): 413-420.

Brown, R.E., (2008), Electric Power Distribution Reliability, **CRC Press**.

Casazza, J. and Delea, F., (2010), Understanding Electric Power Systems, 2nd edition, **John Wiley & Sons, Inc.**, Hoboken, New Jersey.

Celli, G. and Pilo, F., (2001), Optimal Distributed Generation Allocation in MV Distribution Networks, **2001 IEEE PICA conference**, (pp. 81-86).

Chambers, A., (2001), Distributed Generation: a nontechnical guide, **PennWell, Tulsa, UK**.

Chiradeja, P., (2005), Benefit of Distributed Generation: A Line Loss Reduction Analysis, **2005 IEEE/PES Transmission and Distribution Conference and Exhibition: Asia and Pacific**, (pp. 1-5).

Das, D., Kothari, D.P., and Kalam, A., (1995), Simple and efficient method for load flow solution of radial distribution network, **Electrical power and energy system** 17(5): 335-346.

Department of Energy and Climate Change, UK renewable energy roadmap update., (2013),https://www.gov.uk/government/uploads/system/uploads/attachment_data/file255182/.

Dinakara Prasad Reddy, P., Veera Reddy, V. C., and Gowri Manohar., (2017), Whale Optimization Algorithm for Optimal Sizing of Renewable Resource for loss Reduction in Distribution Systems, **Renewables: Wind, Water, and Solar**.

Dondi, P., Bayoumi, D., Haederli, C., Julian, D., and Suter, M., (2002), Network Integration of Distributed Power Generation, **Journal of Power source** 106: 1-9.

Dulau, I. L., Abrudean, M. and Bica, D., (2015), Optimal Location of a Distributed Generator for Power losses Improvement, **9th International Conference Interdisciplinary in Engineering, INTER-ENG 2015**, 8-9 October, Tirgu-Mures, Romania.

El-Hawary, M. E., (2008), Introduction to Electrical Power Systems, **John Wiley & Sons.**

El-Khattam, W., and Salama, M.M.A. (2004). Distributed generation technologies, definitions and benefits. **Electric Power Systems Research**. 119–128, Waterloo, Ont, Canada.

Fernández, A., (2011), Impact of Distributed Generation on Distribution system, **Master Thesis**, Aalborg University, Aalborg, Denmark.

Gandomkar, M., Vakilian, M., and Ehsan, M., (2005), Optimal Distributed Generation Allocation in Distribution Network Using Hereford Ranch Algorithm, **Electrical Machines and Systems, ICEMS 2005**, (pp. 914-918).

Guerriche, K.R., and Boutir, T., (2015), Optimal Location and Sizing of Distributed Generation with Particle Swarm Optimization Algorithm for Loss Reduction, **Revue des Science et de la Technologie-RST**, 6: 59-67.

Haibo, Z., Lizi, Z., and Fanling, M., (1998), Reactive power optimization based on genetic algorithm, **International Power Conference on Power System Technology**, (pp.18-21).

Han, J., Seo, H. C., and Kim, C. H., (2012), Analysis of Lightning Overvoltage According to the Location of Overhead Ground Wire in Korea Distribution System, **2012 IEEE Vehicle Power and Propulsion Conference (VPPC), Seoul, Korea**, (pp. 1274-1276).

Hussian, I., and Roy, A. K., (2012), Optimal distributed generation allocation in distribution system employing modified artificial bee colony algorithm to reduce loss and improve voltage profile, **IEEE- International Conference on Advance in Engineering, Science and Management (ICAESM -2012)**, (pp. 565-570).

IEEE Std 1410-2010., (2011), IEEE Guide for Improving for the Lightning Performance of Electric Power Overhead Line.

Jafari, A., Tabatabaei., and Boushehri, N. S., (2016), Reactive power optimization using intelligent search algorithms considering voltage stability index. **International Journal on "Technical and Physical Problem of Engineering"**, 8: 1-8.

Karaboga, D., and Basturk, B., (2007), On the performance of the artificial bee colony (ABC) algorithm, **Applied soft computing**, 8: 687-697.

Leeton, U., Uthitsunthorn, D., Kwannetr, U., Sisuphun, N., & Kulworawanichpong, T. Power Loss Minimization Using Optimal Power Flow Based on Partical Swarm Optimization.

Lorestani, A., Mohammadian, M., Aghaee, S. S., Ardehali, M. M., and Gharehpetian, G. B., (2016), A Novel Analytical-Heuristic Approach for Placement of Multiple Distributed Generation in Distribution Network, **2016 Smart Grid Conference (SGC), 20-21 Dec. 2016**, (pp. 123-129), Kerman, Iran.

Mehta, P., Bhatt, P., and Pandya, V., (2015), Optimal selection of distributed generating units and its placement for voltage stability enhancement and energy loss minimization, **Ain Shams Eng J (2015)**.

Mishra, A., and Bhandakkar, A., (2014), Selection of Optimal Location and Size of Distributed Generation in Distribution System Using Particle Swarm Optimization, **International Journal of Engineering Research & Technology (IJERT)**, 1: 2008-2013.

Mohamed, D., (2013), Optimal Distributed Generation Placement via Single and Multi- Objective Optimization Approaches, **Master Thesis**, Dalhousie University, Halifax, Nova Scotia.

Moradi, M. H., and Abedinie, M., (2010), A combination of genetic algorithm and particle swarm optimization for optimal DG location and sizing in distribution systems, **2010 Conference Proceedings**.

Morita, S., (2002), Distributed Generation in liberalized electricity markets, **International symposium on distributed generation: power system and market aspects**.

Murthy, V. V. S. N., and Kumar, A., (2014), Mesh Distribution System Analysis in Presence of Distributed Generation within Time Varying Load Model, **International Journal of Electrical Power & Energy System**, 62: 836-854.

Nadhir, k., Chabane, D., and Tarek, B., (2013), Distributed Generation Location and Size Determination to Reduce Power Losses of a Distribution Feeder by Firefly Algorithm, **International Journal of Advanced Science and Technology**, 56: 61-72.

Neto, A. C., Da Silva, M. G., and Rodrigues, A. B., (2006), Impact of Distributed Generation on Reliability Evaluation of Radial Distribution Systems Under Network Constraints, **9th International Conference on Probabilistic Methods Applied to Power Systems**, KTH, Stockholm, Sweden.

Nocedal, J., and Wright, S. J., (1999), Numerical Optimization, **New York: Springer**.

Osaloni, O. O., (2016), Optimal Allocation of Distributed Generation for Power Loss Reduction and Voltage Profile Improvement, **Master Thesis**, University of Cape Town, South Africa.

Pandy, D., and Bhadoriya, J.S., (2014), Optimal Placement and Size of Distributed Generation to Minimize Active Power Loss Using Particle Swarm Optimization, **International journal of scientific and technology research**, 3: 246-254.

Pecas Lopes, A., Hatziargyriou, N., Mutale, J., Djapic. P. and Jenkins, N., (2007), Integrating Distributed Generation into Electric Power Systems: A Review of Drivers, Challenges and Opportunities, **Electric Power Systems Research**, 77: 1189–1203.

Pham, D. T., and Karaboga, D., (1998), Intelligent optimization techniques: Genetic Algorithms, tabu search, simulated annealing and neural networks.

Philip, P., and Barker, R.W., (2011), Determining the Impact of Distributed Generation on Power Systems: Part 1 Radial Distribution Systems, **IEEE Power Engineering Society Summer Meeting**, Seattle, WA.

Prakash, P., and Khatod, D. K., (2016), An Analytical Approach for Optimal Sizing and Placement of Distribution Generation in Radial Distribution Systems, **1st**

IEEE International Conference on Power Electronics, Intelligent Control and Energy System (ICPEICES-2016), (pp. 1-5), Roorkee, India.

Sedighizadeh, M., Fallahnejad, M., Alemi, M. R. Omidvaran, M., and Arzaghi-haris, D., (2010), Optimal Placement of Distributed Generation Using Combination of PSO and Clonal Algorithm, **2010 IEEE International Conference on Power and Energy (PECon2010)**, (pp. 1-6), Nov 29-Dec 1, Kuala Lumpur.

Shaddi, S., and Santoso, D. B., (2016), Optimal Capacity and Placement of Distributed Generation Using Metaheuristic Optimization Algorithm to Reduce Power Loss in Bantul Distribution System, Yogyakarta, **2016 8th International Conference on Information Technology and Electrical Engineering (ICITEE)**, 978-1-5090-4139-8.

Sinsuphun, N., Leeton, U., Kwannetr, U., Uthitsunthorn, D., and Kulworawanichphong, T., (2011), Loss minimization using optimal power flow based on swarm intelligent, **ECTI Transaction on Electrical Eng., Electronic and Telecommunication** 9: 212-222.

So, C. W., and Li, K. K., (2000), Overcurrent relay coordination by evolutionary programming, **Electric power system research**, 53: 83–90.

Subrahmanyam, J. B. V., and Radhakrishna, C., (2009), Distributed Generator Placement and Sizing in Unbalanced Radial Distribution System, **International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering** 3(4): 753-760.

Sumpavakup, C., Srikun, I., and Chusanapiputt, S., (2010), A Solution to the Optimal Power Flow Using Artificial Bee Colony Algorithm, **2010 International Conference on Power System Technology**, 978-1-4244-5940-7.

Uniya, A., and Kumar, A., (2016), Comparison of Optimal DG Allocation based on Sensitivity based and Optimization based Approach, **1st IEEE International Conference on Power Electronics, Intelligent Control, and Energy Systems (ICPEICES-2016)**, (pp. 1-8).

Vita, V., (2016), Electricity Distribution Network's Analysis with Particular References to Distribution Generation and Protection, **PhD Thesis**, City University. United Kingdom.

Vita, V., (2017), Developtment of a Decision-making Algorithm for Optimum Size and Placement of Distributed Generation Units in Distribution Networks. **Energies**, 10: 1433.

Wang, Z., and Xu, Q., (2011), On Distribution System Planning Method for Reliability and its Application, **24th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)**, (pp 1727-1731).

Willis, H. L., (2000), Distributed Power Generation: Planning and Evaluation, **CRC Press**.

Wolpert, D. H., and Macready, W. G., (1997), No Free Lunch Theorem for Optimization, **Evolutionary Computation IEEI Transaction**, 1: 67-82.

Zareipour, H., Bhattacharya, K., and Canizares, C., (2004). Distributed Generation: Current Status and Challenges, **Presented at Proc. 36th Annual North American Power Symposium (NAPS)**.

APPENDIX A

SYSTEM DATA OF THE TESTED SYSTEMS

Table A.1 Line data of 15 bus system.

Branch	Sending node	Receiving node	R (ohm)	X (ohm)
1	1	2	1.353	1.3234
2	2	3	1.1702	1.1446
3	3	4	0.8411	0.8227
4	4	5	1.5234	1.0276
5	2	9	2.0131	1.3579
6	9	10	1.6867	1.1377
7	2	6	2.5572	1.7249
8	6	7	1.0882	0.734
9	6	8	1.2514	0.8441
10	3	11	1.7955	1.2111
11	11	12	2.4484	1.6515
12	12	13	2.0131	1.3597
13	4	14	2.2308	1.5047
14	4	15	1.197	0.8074

Table A.2 Bus data of 15 bus system.

Bus	P (kW)	Q (Kvar)	KVA
1	0.00	0.00	0.00
2	44.10	44.99	63.00
3	70.00	71.41	100.00
4	140.00	142.82	200.00
5	44.10	44.99	63.00
6	140.00	142.82	200.00
7	140.00	142.82	200.00
8	70.00	71.41	100.00
9	70.00	71.41	100.00
10	44.10	44.99	63.00
11	140.00	142.82	200.00
12	70.00	71.41	100.00
13	44.10	44.99	63.00
14	70.00	71.41	100.00
15	140.00	142.82	200.00

Table A.3 Line data of 33 bus system.

Branch	Sending node	Receiving node	R (ohm)	X (ohm)
1	1	2	0.0922	0.047
2	2	3	0.493	0.2512
3	3	4	0.3661	0.1864
4	4	5	0.3811	0.1941
5	5	6	0.819	0.707
6	6	7	0.1872	0.6188
7	7	8	0.7115	0.2351
8	8	9	1.0299	0.74
9	9	10	1.044	0.74
10	10	11	0.1967	0.0651
11	11	12	0.3744	0.1298
12	12	13	1.468	1.1549
13	13	14	0.5416	0.7129
14	14	15	0.5909	0.526
15	15	16	0.7462	0.5449
16	16	17	1.2889	1.721
17	17	18	0.732	0.5739
18	2	19	0.164	0.1565
19	19	20	1.5042	1.3555
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3084
23	24	24	0.898	0.7091
24	24	25	0.898	0.7071
25	6	26	0.2031	0.1034
26	26	27	0.2842	0.1474
27	27	28	1.0589	0.9338
28	28	29	0.8043	0.7006
29	29	30	0.5074	0.2585
30	30	31	0.9745	0.9629
31	31	32	0.3105	0.3619
32	32	33	0.3411	0.5302

Table A.4 Bus data of 33 bus system.

Bus	P (kW)	Q (Kvar)	Bus	P (kW)	Q (Kvar)
1	0	0	18	90	40
2	100	60	19	90	40
3	90	40	20	90	40
4	120	80	21	90	40
5	60	30	22	90	40
6	60	20	23	90	50
7	200	100	24	420	200
8	200	100	25	420	200
9	60	20	26	60	25
10	60	20	27	60	25
11	45	30	28	60	20
12	60	35	29	120	70
13	60	35	30	200	100
14	120	80	31	150	70
15	60	10	32	210	100
16	60	20	33	60	40
17	60	20			

Table A.5 Line data of 69 bus system.

Branch	Sending node	Receiving node	R (ohm)	X (ohm)
1	1	2	0.0005	0.0012
2	2	3	0.0005	0.0012
3	3	4	0.0015	0.0036
4	4	5	0.0251	0.0294
5	5	6	0.366	0.1864
6	6	7	0.3811	0.1941
7	7	8	0.0922	0.047
8	8	9	0.0493	0.025
9	9	10	0.819	0.2707
10	10	11	0.1872	0.0619
11	11	12	0.7114	0.2351
12	12	13	1.03	0.34
13	13	14	1.044	0.345
14	14	15	1.058	0.3496
15	15	16	0.196	0.065
16	16	17	0.3744	0.1238
17	17	18	0.0047	0.0016

18	18	19	0.3276	0.1083
19	19	20	0.2106	0.069
20	20	21	0.3416	0.1129
21	21	22	0.014	0.0046
22	22	23	0.01591	0.0526
23	23	24	0.3463	0.1145
24	24	25	0.7488	0.2475
25	25	26	0.3089	0.1021
26	26	27	0.1732	0.0572
27	3	28	0.0044	0.0108
28	28	29	0.064	0.1565
29	29	30	0.3978	0.1315
30	30	31	0.0702	0.0232
31	31	32	0.351	0.116
32	32	33	0.839	0.2816
33	33	34	1.708	0.5646
34	34	35	1.474	0.4873
35	3	36	0.0044	0.0108
36	36	37	0.064	0.1565
37	37	38	0.1053	0.123
38	38	39	0.0304	0.0355
39	39	40	0.0018	0.0021
40	40	41	0.7283	0.8509
41	41	42	0.31	0.3623
42	42	43	0.041	0.0478
43	43	44	0.0092	0.0116
44	44	45	0.1089	0.1373
45	45	46	0.0009	0.0012
46	4	47	0.0034	0.0084
47	47	48	0.0851	0.2083
48	48	49	0.2898	0.7091
49	49	50	0.0822	0.2011
50	8	51	0.0928	0.0473
51	51	52	0.3319	0.1114
52	9	53	0.174	0.0886
53	53	54	0.203	0.1034
54	54	55	0.2842	0.1447
55	55	56	0.2813	0.1433
56	56	57	1.59	0.5337
57	57	58	0.7837	0.263
58	58	59	0.3042	0.1006

59	59	60	0.3861	0.1172
60	60	61	0.5075	0.2585
61	61	62	0.0974	0.0496
62	62	63	0.145	0.0738
63	63	64	0.7105	0.3619
64	64	65	1.041	0.5302
65	11	66	0.2012	0.0611
66	66	67	0.0047	0.0014
67	12	68	0.7394	0.2444
68	68	69	0.0047	0.0016

Table A.6 Bus data of 69 bus system.

Bus	P (kW)	Q (Kvar)	Bus	P (kW)	Q (Kvar)
1	0	0	36	0.026	0.0185
2	0	0	37	0	0
3	0	0	38	0.024	0.017
4	0	0	39	0.024	0.017
5	0.0026	0.0022	40	0.0012	0.001
6	0.0404	0.03	41	0	0
7	0.075	0.054	42	0.006	0.0043
8	0.03	0.022	43	0	0
9	0.28	0.019	44	0.009	0.0263
10	0.145	0.104	45	0.039	0.0263
11	0.145	0.104	46	0	0
12	0.008	0.005	47	0.079	0.0564
13	0.008	0.0055	48	0.3847	0.2745
14	0	0	49	0.3847	0.2745
15	0.0455	0.03	50	0.0405	0.0283
16	0.06	0.035	51	0.0036	0.0027
17	0.06	0.035	52	0.00435	0.0035
18	0	0	53	0.0264	0.019
19	0.001	0.0006	54	0.0244	0.0172
20	0.114	0.081	55	0	0
21	0.005	0.0035	56	0	0
22	0	0	57	0	0
23	0.028	0.002	58	0.1	0.072
24	0	0	59	0	0
25	0.014	0.001	60	1.244	0.88
26	0.014	0.001	61	0.032	0.023
27	0.026	0.018	62	0	0
28	0.026	0.018	63	0.227	0.162
29	0	0	64	0.059	0.042

30	0	0	65	0.018	0.013
31	0	0	66	0.018	0.013
32	0.014	0.001	67	0.028	0.02
33	0.0195	0.014	68	0.028	0.02
34	0.006	0.004	69	0	0
35	0.026	0.0185			

Table A.7 Line data of 85 bus system.

Branch	Sending node	Receiving node	R (ohm)	X (ohm)
1	1	2	0.108	0.075
2	2	3	0.163	0.112
3	3	4	0.217	0.149
4	4	5	0.108	0.074
5	5	6	0.435	0.298
6	6	7	0.272	0.186
7	7	8	1.197	0.82
8	8	9	0.108	0.074
9	9	10	0.598	0.41
10	10	11	0.544	0.373
11	11	12	0.544	0.373
12	12	13	0.598	0.41
13	13	14	0.272	0.186
14	14	15	0.326	0.223
15	2	16	0.728	0.302
16	3	17	0.455	0.189
17	5	18	0.82	0.34
18	18	19	0.637	0.264
19	19	20	0.455	0.189
20	20	21	0.819	0.34
21	21	22	1.548	0.642
22	19	23	0.182	0.075
23	7	24	0.91	0.378
24	8	25	0.455	0.189
25	25	26	0.364	0.151
26	26	27	0.546	0.226
27	27	28	0.273	0.113
28	28	29	0.546	0.226
29	29	30	0.546	0.226
30	30	31	0.273	0.113
31	31	32	0.182	0.075
32	32	33	0.182	0.075
33	33	34	0.819	0.34
34	34	35	0.637	0.264

35	35	36	0.182	0.075
36	36	37	0.364	0.151
37	37	38	1.002	0.416
38	38	39	0.546	0.226
39	39	40	0.455	0.189
40	40	41	1.002	0.416
41	41	42	0.273	0.113
42	41	43	0.455	0.189
43	34	44	1.002	0.416
44	44	45	0.911	0.378
45	45	46	0.911	0.378
46	46	47	0.546	0.226
47	35	48	0.637	0.264
48	48	49	0.182	0.075
49	49	50	0.364	0.151
50	50	51	1.366	0.189
51	48	52	0.455	0.567
52	52	53	0.546	0.189
53	53	54	0.546	0.226
54	52	55	0.546	0.226
55	49	56	0.273	0.226
56	9	57	0.819	0.113
57	57	58	0.182	0.34
58	58	59	0.546	0.075
59	58	60	0.728	0.226
60	60	61	0.182	0.302
61	61	62	0.182	0.415
62	60	63	0.455	0.075
63	63	64	0.91	0.302
64	64	65	0.182	0.075
65	65	66	0.182	0.075
66	64	67	0.455	0.189
67	67	68	0.91	0.378
68	68	69	1.092	0.453
69	69	70	0.455	0.189
70	70	71	0.546	0.226
71	67	72	0.182	0.075
72	68	73	1.184	0.491
73	73	74	0.273	0.113
74	73	75	1.002	0.416
75	70	76	0.546	0.226
76	65	77	0.091	0.037
77	10	78	0.637	0.264
78	67	79	0.546	0.226

79	12	80	0.728	0.302
80	80	81	0.364	0.151
81	81	82	0.091	0.037
82	81	83	1.092	0.453
83	83	84	1.002	0.416
84	13	85	0.819	0.34

Table A.8 Bus data of 85 bus system.

Bus	P (kW)	Q (Kvar)	Bus	P (kW)	Q (Kvar)
1	0.00	0.00	44.00	35.28	35.99
2	0.00	0.00	45.00	35.28	35.99
3	0.00	0.00	46.00	35.28	35.99
4	56.00	57.12	47.00	14.00	14.28
5	0.00	0.00	48.00	0.00	0.00
6	35.28	35.99	49.00	0.00	0.00
7	0.00	0.00	50.00	35.28	35.99
8	35.28	35.99	51.00	56.00	57.12
9	0.00	0.00	52.00	0.00	0.00
10	0.00	0.00	53.00	35.28	35.99
11	56.00	57.12	54.00	56.00	57.12
12	0.00	0.00	55.00	56.00	57.12
13	0.00	0.00	56.00	14.00	14.28
14	35.28	35.99	57.00	56.00	57.12
15	35.28	35.99	58.00	0.00	0.00
16	35.28	35.99	59.00	56.00	57.12
17	112.00	114.24	60.00	56.00	57.12
18	56.00	57.12	61.00	56.00	57.12
19	56.00	57.12	62.00	56.00	57.12
20	35.28	35.99	63.00	14.00	14.28
21	35.28	35.99	64.00	0.00	0.00
22	35.28	35.99	65.00	0.00	0.00
23	56.00	57.12	66.00	56.00	57.12
24	35.28	35.99	67.00	0.00	0.00
25	35.28	35.99	68.00	0.00	0.00
26	56.00	57.12	69.00	56.00	57.12
27	0.00	0.00	70.00	0.00	0.00
28	56.00	57.12	71.00	35.28	35.99
29	0.00	0.00	72.00	56.00	57.12
30	35.28	35.99	73.00	0.00	0.00
31	35.28	35.99	74.00	56.00	57.12

32	0.00	0.00	75.00	35.28	35.99
33	0.00	0.00	76.00	56.00	57.12
34	0.00	0.00	77.00	17.00	17.34
35	0.00	0.00	78.00	56.00	57.12
36	35.28	35.99	79.00	35.28	35.99
37	56.00	57.12	80.00	56.00	57.12
38	56.00	57.12	81.00	0.00	0.00
39	56.00	57.12	82.00	56.00	57.12
40	35.28	35.99	83.00	35.28	35.99
41	0.00	0.00	84.00	14.00	14.28
42	35.28	35.99	85.00	35.28	35.99
43	35.28	35.99			

BIOGRAPHY

Sovann Ang was born in Kampot province, Cambodia. He received B. Eng in Electrical Engineering from Institute of Technology of Cambodia in 2015. Then, he pursued to Master degree of Electrical Engineering at Suranaree University of Technology, Nakhon Ratchasima, Thailand in 2016. His fields interested in the research include optimal power flow in power transmission, and currently he is focusing on optimal distributed generation in radial distribution network.