OPTIMAL SITING AND SIZING OF DISTRIBUTED GENERATORS (DGs) IN ACTIVE DISTRIBUTION NETWORK (ADN) CONCEDING POWER LOSSES AND VOLTAGE DEVIATION

by

Abduladheem Almalki (Abdu)
B.Sc., Riyadh College of Technology, 2011

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

In recent years, Smart Grid Technology (SGT) has become the next generation of communication and control techniques in power grids, which provides bi-directional communication and control of power flow to enhance the power supply capability and reliability to a power network. One of the most important competent of SGT is the Distributed Generations (DGs) that are interconnected into the Distribution System (DS) to incorporate renewable energy sources into the power grid, to reduce power losses in transmission, and to improve grid voltage quality or stability. In fact, installing DGs might cause negative impacts on the grid, such as increasing power loss, operation costs, and poor voltage profile. Hence, proper design of DS, including optimal siting and sizing the DGs at appropriate location and with proper capacity play an important role in SGT. This work aims at finding the optimal locations and sizes of DGs in the power grid, using the IEEE 57-bus network as a test case. The tasks are accomplished by formulating an optimization problem for minimizing the active power losses under acceptable grid voltage variation and solving the Global Optimization (GO) problem using Metamodel-Based GO method. The power network model are built in MatPower, and the network simulation and optimization are carried in MATLAB with MatPower interface. Results for the modeling, simulation and optimization are presented to show the benefit of the proposed method.
Contents

Supervisory Committee ii

Abstract iii

Table of Contents iv

List of Tables vii

List of Figures viii

Acknowledgements ix

Dedication x

1 Introduction 1
  1.1 Smart Grid Technology (SGT) 1
  1.2 Distributed Generation (DG) 1
  1.3 Motivation and Research Objectives 2
  1.4 Contributions 2
  1.5 Thesis Organization 2

2 Smart Grid Technology (SGT) and Related Work 3
  2.1 Background of Smart Grid Technology (SGT) 3
     2.1.1 General Features of Smart Grid Technology 4
     2.1.2 Differences Between Traditional Power Grid and SGT 5
  2.2 Network System and Components of Smart Grid 6
     2.2.1 Energy Management System 7
     2.2.2 Smart Meter 8
     2.2.3 Smart Appliances 9
     2.2.4 Electric Vehicle (EV) 9
2.2.5 Home Electricity Generation and Storage 10
2.2.6 Smart Consumption 10
2.2.7 Smart Power Generation 11
2.2.8 Smart Transmission 12
2.3 Distributed Generation (DG) 13
  2.3.1 Types and Sizes of DGs 13
  2.3.2 Potential Benefits of DGs 13
  2.3.3 Challenges of DGs 14
2.4 Operation of Power Network and Its Optimization 15
2.5 Various Optimization Algorithms for Smart Grid Optimal Control 15
  2.5.1 Classic Global Optimization Methods 15
  2.5.2 Metamodel-Based Global Optimization Methods (MBGO) 17

3 GENERAL PROBLEM 20
  3.1 Simulation Model and Distribution Network 20
    3.1.1 Matpower 20
    3.1.2 MATLAB 21
  3.2 Proposed Methods 21
  3.3 Formulation of Optimal Operation Problem 22
    3.3.1 Objective Function 22
    3.3.2 Constrains 23
  3.4 A Test Example of Distribution Network with DG IEEE-57 Bus 24

4 Optimal Network Operation under Different Conditions 27
  4.1 Power Loss Reduction and Voltage Variation 28
    4.1.1 Case I; Installing A Single DG 28
    4.1.2 Case II; Installing Two DGs 28
    4.1.3 Case III; Installing Three DGs 29
    4.1.4 Case IV; Installing Four DGs 30
    4.1.5 Case V; Installing Five DGs 31
    4.1.6 Case VI; Installing Six DGs 31
  4.2 Computational Time Comparison 33
  4.3 Number of Function Evaluation 33

5 Summary 35
  5.1 Summary of this Work 35
List of Tables

Table 2.1 Comparison between Smart Grid and Traditional Grid [1] . . . . 6

Table 4.1 Comparison results of each case and algorithm’s performance. . 34
List of Figures

Figure 2.1 Smart Grid concept [2] ........................................ 4
Figure 2.2 power system ..................................................... 7
Figure 2.3 Energy management system ............................... 8
Figure 2.4 Smart meter ....................................................... 9
Figure 2.5 Smart generation and storage .............................. 10
Figure 2.6 Methods of Communication ................................. 12
Figure 2.7 Generic Algorithm flow chart. ............................. 16

Figure 3.1 MATLAB and Matpower interface. ....................... 22
Figure 3.2 IEEE 57 bus system. ........................................... 25
Figure 3.3 Base case voltage profile. ................................... 26

Figure 4.1 Voltage profile $pu$. ........................................ 28
Figure 4.2 Voltage profile $pu$. ........................................ 29
Figure 4.3 Voltage profile $pu$. ........................................ 30
Figure 4.4 Voltage profile $pu$. ........................................ 30
Figure 4.5 Voltage profile $pu$. ........................................ 31
Figure 4.6 Voltage profile $pu$. ........................................ 32
Figure 4.7 Power losses for all the cases $MW$. ..................... 33
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DEDICATION

To my parents and my wife Asma as well as my lovely son Raif.
To all my brothers and sisters
Chapter 1

Introduction

1.1 Smart Grid Technology (SGT)

Since the global warming has been increasing nowadays due to massive growing in the world population, increasing of carbon emissions, and rising of power demands, the conventional power grid has been integrated to become more intelligent grid named Smart Grid Technology (SGT) [3]. It is simply defined as an intelligent electrical network where the electricity can be driven into two ways of flow and communication resulting in robust, secure, flexible, reliable, and efficient electric system. One of the essential benefit of SGT is to enable integration of single or multiple distributed generation (DGs) into the distribution system (DS) to reduce power losses and improve voltage quality and stability [4]. The location and size of DGs may lead to positive or negative impact on the network. Therefore, this thesis mainly focuses on finding the optimal placement and capacity of DG into the DS.

1.2 Distributed Generation (DG)

As the SGT is implanted on the distribution system, Distributed Generation (DG) is one of the critical component of the distribution system. DG can be simply defined as a source that placed close to users or the point of consumption to improve power quality and reduce the power losses. DG might be either renewable power source, such as photo-voltaic, wind, and biomass, or non-renewable power source such as fuel cells, natural gas, and micro-turbines. DG can be implemented on residential, industrial, and commercial areas and it can be operated as primary source, standby, or a source
for reactive power. As a result, the distribution system enhanced by placing DG in an optimal location with respect optimal capacity of DG.

1.3 Motivation and Research Objectives

The primary goal of this project is to introduce SGT, DG, and optimization methodologies of finding the optimal size and location of DGs. These methods are applied on IEEE 57-bus test cases using MATLAB and Matpower environment. The proposed method is to use different optimization algorithms to reduce power losses and improve voltage profile by installing a single or multiple DGs into the system.

1.4 Contributions

In this project, the key design optimization problem of DG has been identified, and the appropriate power grid modeling and simulation tool has been used to gauge the performance of the network. A method for obtaining the optimal siting and sizing of single and multiple DGs has been introduced. After comparing various GO algorithms, and the best and suitable GO search algorithm for this application has been identified. Using the newly introduced optimization formulation the optimal number of DGs installation has been identified. The new method is able to reduce grid power loss and maintain acceptable voltage stability.

1.5 Thesis Organization

Chapter 1 introduces SGT, and DG; Chapter 2 presents an overview of SGT’s components and related work; Chapter 3 discuss the network simulation tool, the proposed method, and formulation of the optimization problem; Chapter 4 shows the results of the network simulation and optimization and their discussions. Finally Chapter 5 presents the conclusion and future work.
Chapter 2

Smart Grid Technology (SGT) and Related Work

2.1 Background of Smart Grid Technology (SGT)

A conventional power system that uses a unidirectional way has become inadequate in recent years as a new technology has emerged. The major problem with the traditional power system is that it generates energy from non-renewable sources such as coal or natural gas, which harms the environment. Secondly, the unidirectional grid system is not reliable, it wastes power, and it limits a variety of sources and the systems control of distribution. Therefore, Smart Grid Technology (SGT) has been developed to promote the emergence of renewable energy and to enhance the efficiency of power distribution [5].

However, the industry is facing new challenges of applying SGT and meeting the demand of consumers who expect low cost and high performance. In this case, the SGT system improves the reliability of electricity distribution, generation, transmission, protection, and control. Therefore, the technology can enhance the efficiency of power generation and the distribution system [5]. The principle of SGT is to combine entire electricity generation and distribution systems in a single structure or system that can control and supply power and facilitate communication between generators and consumers. In other words, SGT is a complex implementation of computer intelligence to an existing electricity system using networking facilities. As a result, SGT seeks to implement emergent technology to upgrade the traditional grid system, making it smarter and cleaner [5]. In recent decades, it has become apparent
that generating clean energy is essential to protect the environment and to decrease our dependency on oil. The main purpose of SGT is to make all components of the grid work automatically and remotely leading to an extraordinary enhancement of reliability, efficiency, and flexibility [2]. Accordingly, SGT provides many benefits for both suppliers and consumers; these include effective transmission of power, a decrease in peak demand, and self-healing control to avoid outage or shortage. SGT also facilitates the emergence of renewable energy sources such as the wind and solar power.

![Smart Grid concept](Figure 2.1)

2.1.1 General Features of Smart Grid Technology

SGT is considered one of the most important technologies in the world because of its many valuable features. SGT promotes the introduction of natural and renewable energy that is sustainable and environmentally friendly. Natural and renewable sources include solar, wind, wave, hydro, geothermal, and biomass. As these sources are introduced, it is important to integrate SGT to make the best use of them [6]. The following are the essential and common features of SGT:
• Create a sense of balance between power generation and demand of electricity. This might be done via disseminated storage, demand feedback, advanced sensing, control software, information infrastructure, and market signals.

• Enable renewable energy that can coordinate and control a power flow system simultaneously resulting in better levels of integration of renewable resources to reach higher efficiencies and lower costs.

• Use bi-directional ways of communication which can employ feedback to the supplier regarding consumption, distribution, and outage. This can be done by using Advanced Metering Instruments (AMI) and internet-based services [6].

• Improve power reliability and quality by easily find the point of failure through sensors.

• Reduce the emissions by enabling electric vehicles and transportation.

• Improve the efficiency and capacity of existing power networks.

• Enable self-repair or healing responses to system disturbances.

• Conduct operations through the automatic control system.

• Reduce oil consumption by decreasing the needs for an inefficient generation while in peak demand [1].

2.1.2 Differences Between Traditional Power Grid and SGT

Traditional Power Grid (TPG) has only one-way communication between suppliers and customers that makes it incapable of giving real-time data to utilities and clients regarding consumption or demand response. TPG cannot manage the precise generation and distribution between supplier and customer [5]. Due to the lack of an accurate control system in the TPG, it is easy to steal electricity from any point of the grid system without any recognition of an electricity supplier. That is one reason that power loss is unpredictable, and thus, generation failed to meet the expectation of demand for consumption. Another issue is a lack of safety; there are very limited instruments to figure out the fault in any system and minimize the blame. Finally, if an error occurs in the TPG, it might black out an entire area until the fault is diagnosed and fixed manually. In contrast, SGT is capable of managing the two-way
communication of power and data to improve performance, and reach the desired demand. Furthermore, SGT can easily figure out problems and fix them, or avoid them automatically, such as power outage, failure, and power loss [7]. Table 2.1 shows some comparisons between SGT and TPG.

Table 2.1: Comparison between Smart Grid and Traditional Grid [1]

<table>
<thead>
<tr>
<th>Traditional Grid</th>
<th>Smart Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromechanical</td>
<td>Digital</td>
</tr>
<tr>
<td>One-way communication</td>
<td>Two-way communication</td>
</tr>
<tr>
<td>Centralized generation</td>
<td>Distributed generation</td>
</tr>
<tr>
<td>Few sensors</td>
<td>Sensors throughout</td>
</tr>
<tr>
<td>Manual monitoring</td>
<td>Self-monitoring</td>
</tr>
<tr>
<td>Manual restoration</td>
<td>Self-healing</td>
</tr>
<tr>
<td>Failures and blackouts</td>
<td>Adaptive and islanding</td>
</tr>
<tr>
<td>Limited control</td>
<td>Pervasive control</td>
</tr>
<tr>
<td>Few customer choices</td>
<td>Many customer choices</td>
</tr>
</tbody>
</table>

2.2 Network System and Components of Smart Grid

An electric power system contains three main components called generation, transmission lines, and distribution system. The generated electricity is delivered to consumers from generation to distribution system via transmission lines. The generation is defined as a producer or provider of the electricity to a point of consumption such as industry, resident, or commercial areas. The voltage level is increased or decrease through transformers. The common range of generated electricity power is between 11KV to 25 KV and then the voltage is stepped up by the main sub-station to reach between 66 KV to 400 KV or higher. The main idea of stepping up is to reduce the power losses in the transmission lines. At the main feeder of distribution system, the voltage is stepped down to 132 KV or less. In the DS, the voltage level is reduced to 13 KV to supply the final consumer feeders at 400 V which gives 230 V per phase.
Figure 2.2: power system

The traditional power grid consists of one centralized power source among an individual grid, however, a smart grid contains multiple sources in the same grid. These sources include coal, hydro, nuclear, natural gas, and distributed generator (DG). The following is highlight of the main components of SGT.

2.2.1 Energy Management System

The Energy Management System (EMS) is a core device in a smart home. It is used to receive a certain amount of consumed data as input from the smart meter. From this system, the real-time data presents how much energy has been consumed, and it could be shown to computers or mobile devices that enable consumption management and reduction. Based on this energy management system, consumers can know more details about their consumption of each smart appliance such as air condition, dishwasher, and heaters. Moreover, consumers would have the ability to control smart appliances by turning them on, or off remotely. Also, the EMS displays real-time electricity prices to consumers, allowing consumers to adjust their smart appliances to turn off automatically on high demand to avoid an outage or peak demand rates. However, when the electricity price is lower, the smart appliances are turned on automatically by EMS, which allows to balance the energy load and avoid blackouts, or overload electricity [8].
2.2.2 Smart Meter

A smart meter is a significant element of the smart home because it is dependable for measuring actual consumption and power generation. Using smart or digital metering allows customers to monitor their daily energy consumption in real time. In other words, a smart meter is a measurement tool that measures the electricity consumed by the customers. It usually reads the data after a certain time, or a few times per day, and then send the data to the operator to analyze it. This can be helpful for consumers to understand more details about their billing procedures and usage of electricity. Therefore, they can easily maintain and control the usage of electricity according to their desired billing limit and budget. Additionally, the smart meter helps providers to calculate the actual bills regarding how much electricity is being used by consumers [5]. Figure 2.4 is an example of the smart meter.
2.2.3 Smart Appliances

In smart homes that contain many different smart appliances such as air conditioners, heaters, dishwashers, pool pumps, and Electric Vehicles (EV) is a particular network that is controlled by EMS based on consumers preferences. This means EMS has the ability to manage, schedule, and control all the smart appliances automatically and remotely. For example, air conditioner or heater can be switched on, or off, before arriving, or after leaving the home. Similarly, a smart refrigerator might delay its running cycle until off-peak hours, or a smart dishwasher might defer running until off-peak hours. This could reduce the overall consumption of electricity. Moreover, smart appliances can respond to signals that come from the energy provider to avoid using energy during the time of peak demand. This can be done through different techniques; for instance, extending the cycle time of a smart air conditioner slightly can reduce the load on the grid. Therefore, if millions of air conditioners use the same method, it would significantly reduce the total load on the whole power grid [9].

2.2.4 Electric Vehicle (EV)

EV is also considered one of smartest appliances which is designed with a two-way electric power supply system. This system can feed the power either from home to vehicle, or vehicle to home. With this new method, the supplement that comes from home solar energy or wind turbine, and charging during off-peak demand, the electricity can be stored in a EVs battery. Once the energy is stored, it can be used to supply the house during peak demand times, or an emergency situation such as an outage. This can be done by the Energy Management System (EMS). In the case of a blackout, the batteries of Prius Plug-in Hybrid Vehicles (PHVs) can be helpful to
power an average Japanese house for approximately four days with a full tank of fuel and a fully charged battery [10].

2.2.5 Home Electricity Generation and Storage

A smart home can generate local energy by using solar panels, or small wind turbines to provide an extra renewable energy source. Consequently, this can reduce electric bills and consumption produced by a provider. The smart meter measures locally produced energy and the homes consumption and then provides the differences to consumers and provider [8]. However, if a consumers production is more than homes consumption, it might be either sold to the electricity provider or stored in batteries at home and used it later when peak-demand times occurs or in emergency situations such as blackout [9].

Figure 2.5: Smart generation and storage

2.2.6 Smart Consumption

SGT provides an intelligent way of consumption for both energy provider and consumer. It can be done by distributing the energy effectively from both sides (provider and consumers). A provider should supply adequate energy based on demand resulting in a reduction of power loss and costs. Demand Response (DR) programs
and Active Demand-Side Management (ADSM) are the best solutions to balance and maintain power flow. The following two elements describe more details about DR and ADSM [9].

**Demand-side Response Programs**

A supplier provides different programs to encourage consumers to change their patterns of behavior regarding consumption. One of these programs is based on financial incentives. For example, demand reward programs allow consumers to sell the electricity to their suppliers if they can produce more than they consume, otherwise they can use it on peak demand, or in the case of an outage. Another program is a dynamic price program that has volatile prices based on peak demand times such as on the weekends. In fact, high energy bills have influenced people to reduce their consumption [9].

**Active Demand-Side Management**

The concept of Active Demand-Side Management (ADSM) comes from the combination of Demand-Side Management (DSM) and home automated control demand. ADSM enables consumers to modify their demand profile that lead to a reduction of load electricity, and maximization of self-consumption once the renewable source is available. Thus, ADSM contributes benefits such as reducing power losses and loads shedding among the grid, and decreasing energy bills [11].

**2.2.7 Smart Power Generation**

The basic concept of generating electricity in the 1820s, which was discovered by Michael Faraday, is still being used today. Based on his method, electricity can be produced by rotating a copper disc, or a loop of wire between magnetic poles. To make this rotation, there are a lot of different sources which can be used such as coal, natural gas, the sun, wind, ocean waves, and nuclear power. Some of these sources have had an adverse impact on the environment and economic growth. However, Smart Power Generation (SPG) contributes in a positive way to the environment, energy providers, and consumers. SGT enables two-way flows of electricity that can play a significant role regarding generated and distributed energy. Thus, renewable energy like solar panels, or wind turbines, can be easily installed into the network of SGT resulting in an increase of energy, reduction of peak-demand times and the costs
to the consumer [1]. There are some advantages of implementing smart distributed
generation such as: the reduction of environmental effects, decreased time of deploy-
ment, diversification of the energy matrix, and the improvement in grid reliability. In
contrast, in order to apply smart distribution, some difficulties have been encountered
such as the complexity of delivering the flow of two-way electricity, and the high cost
of changing electric equipment such as the smart meter or wireless sensors [9].

2.2.8 Smart Transmission

The transmissions networks of SGT has built on the traditional power system by
adding some equipment such as a control system and communication systems. There-
fore, the intelligent transmission has automated substations and management systems
among the grid resulting in accurate and secure data [1]. In order to improve the con-
trol system, utilities have synchronized data to maintain the power flow and distribu-
tion automatically between suppliers and consumers. This can enable some valuable
features like real-time monitoring, and self-healing. To make an efficient communica-
tion system, there are a lot of methods involved which, according to Electric Power
Research Institute (EPRI) [12], includes direct sensors, storage and collection, daisy
chain, wireless mesh, and a wireless hub. Figure 2.6 illustrates the structures of
sensors that are controlled by a variety of ways.

Figure 2.6: Methods of Communication
2.3 Distributed Generation (DG)

As the SGT is implanted into the distribution system, Distributed Generation (DG) is one of the critical components of the distribution system. DG can be simply defined as a source that placed close to users or the point of consumption to improve power quality and reduce power losses. DG might be either renewable power source, such as photo-voltaic, wind, and biomass, or non-renewable power source such as fuel cells, natural gas, and micro-turbines. DG can be implemented on residential, industrial, and commercial areas and it can be operated as primary source, standby, or a source for reactive power. Therefore, the distribution system enhanced by placing DG in an optimal location with respect an optimal capacity of DG.

2.3.1 Types and Sizes of DGs

There are four main types of DG that can be classified in terms of the capability to deliver the real and reactive power. The first type is capable to inject the real power only and it called type-P. Photo-voltaic, fuel cells, and micro turbines are considered as type-P. The second type is capable to inject reactive power only and it called type Q. The third type is capable to supply both real power and reactive power and it called PQ+ type. The last one is capable to inject real power and absorb reactive power from the grid and this type called PQ- [13].

The size of DG is determined based on how much energy will generate and according to [13], there are four sizes of DG. The smallest one is call micro DG which is capable to generate between 1 to 5 KW. Followed by small DG and it able to generate between 5 KW to 50 MW. The next size is called medium DG which can generate between 5 MW to 50 MW. The last one is large size and its ability of generation rated between 50 MW to 300 MW.

2.3.2 Potential Benefits of DGs

If the DGs installed in proper location and size, they will come up with the following benefits:

1. Improve the voltage profile.

2. Significant reduction of losses of the system.

3. Due to generating near the load, the stress on transmission systems is reduced.
4. Renewable energy is very environmentally friendly, so does not have emissions.

5. Very good choice for rural areas where the costs of transmission is very high.

6. Modular DG units can be easily and quickly installed by utilities and customers.

7. DGs can relieve the overloads of feeders.

8. They can improve system reliability and power quality.

9. As the DGs increase the efficiency while the price decreases, they become more attractive choices for power generation in the future.

10. DGs investment risk is low leading to time is short.

11. Small scale modular DG units can track load variations closely.

12. DG units are small, so they do not need much space, unlike centralized plants.

13. Through environmental improvement, DGs reduce health care costs.

### 2.3.3 Challenges of DGs

1. Islanding of DG may cause over-voltage or voltage flicker.

2. Controlling of customer-owned DGs seems to be challenging.

3. Controlling non-dispatchable output such as PV or wind make it challenging.

4. If the DGs not in optimal place and size may cause over-voltage, excessive power losses, and stability issues.

5. DGs may inject harmonics into the electric system.

6. Bi-directional power flows may increase short circuit currents.

The major reasons of finding optimal DG units are:

- Improve power quality and reliability.
- Decrease the cost of operational investment
- Decrease the harmfulness of the environment.
2.4 Operation of Power Network and Its Optimization

Nowadays, the conventional network system has developed to become more intelligent by installing various sources into the system. Distributed Generator (DG) is one of the essential element that contribute significant improvement of the network. The main reason of this improvement is that the source become close to the consumer and thus there will be noticeable reduction of power losses and having more reliable system. In order utilize DGs into the network, the optimal location and size of DGs is primary object of this project which can be obtained by solving optimal power flow problem (OPF). The OPF problem can be solved via two main methods include conventional optimization methods and stochastic(metaheuristic) global optimization methods [14].

Non-Linear Programming (NLP), Quadratic Programming (QP), Linear Programming (LP), Gradient Method, Newton Method, and Interior Point Method (IPM) are considered as the conventional optimization methods. In this regard, the OPF problem has complex models that make the conventional optimization methods are not applicable to solve OPF due to nonlinear objective function and constraints as well as non-differentiable equations [14]. Therefore, population-based of global optimization method are used to solve the OPF for optimal siting and sizing DGs. In this project four different algorithms are chosen to solve OPF and then compared to find out the best method. These methods can solve; nonlinear objective and constrains functions, and mixed types of variables which can be achieved by using sampling data into design space.

2.5 Various Optimization Algorithms for Smart Grip

2.5.1 Classic Global Optimization Methods

Genetic Algorithm (GA)

Genetic Algorithm (GA) is a method that used for solving global optimization problems which based on Darwins’s theory of evolution. This method uses natural selection process based on mimicking evolutionary biology techniques. The typical rou-
The flowchart of GA starts with an initial generation of candidate solutions that are evaluated against the objective function. At each iteration, the GA randomly selects candidates from the current population and consider them as parents to produce children for a new generation [15]. The process of generating a new generation are done via crossover and mutation technique. Crossover splits two chromosomes and combine one half of each chromosome with the other pair. However, mutation flips a single bit of a chromosome to avoid getting stuck in local minima. After that, the chromosomes are evaluated by the fitness criteria, then the decision made either keeping the best ones or discarding the others chromosome. These process repeats until reaching either optimal solution of the problem or the limit of stopping criteria as shown in Figure 2.7. GA can be used for either constrained or unconstrained optimization problems as well as linear and nonlinear problems. In addition to that, GA perform global optimal solution for discontinuous objective function that has several local minima.

![Figure 2.7: Generic Algorithm flow chart.](image)

**Simulated Annealing (SA)**

Simulated Annealing (SA) is a heuristic technique that inspired form physical process of heating and cooling material named annealing which based on an analogy to the statistical mechanics of disordered system. SA was introduced in 1983 by Kirkpatrick and it used to find global optimal solution for NP optimization problem. Typically, the physical process of annealing is to heat metal to reach certain level of temperature and then cool it down upon a particular rate, thus, the metals properties will be modified [16]. Hence, SA uses the same technique by considering two variables named...
temperature $T$, which represents heating process, and as the cooling rate. SA starts the search space with high temperature and evaluate the objective function. As the temperature is high, it will accept solutions that worse than the current solution which leads to jump out from local optimum. As the temperature is decreased, SA algorithm gradually focus on a certain area that close to optimum solution which makes SA as remarkably effective in finding optimum solution even with large problems [17]. SA uses the concept of iterative improvement which accepts higher cost trial points and they determined by Boltzmann distribution probability. At high temperatures, the chance of accepting uphill move is large and, once the temperatures decreased, the probability of accepting uphill is small.

$$P[acceptX_t] = e^{\frac{f(X_t) - f(X_0)}{CT}}$$

(2.1)

According the above equation, $X_0$ represents the initial starting point whereas the probability is compared with generated random number over range of $[0..1]$. If $P$ is greater or equal than the random number of $[0..1]$, the trial point is accepted. SA repeats the iterative improvement until the global optimal is reached [18].

### 2.5.2 Metamodel-Based Global Optimization Methods (MBGO)

Metamodel-Based Global Optimization Methods (MBGO) are considered as one of the effective and robust technique that solve complex global engendering design optimization problems that evaluate given objective functions. By using this technique, the high computation cost can be reduced as well as repeating evaluation of objective functions and constrains can be avoided. It can be done by exploring the design space in optimal way in which identifying the most effective promising search regions and deleting or ignoring the less promising regions towered to determine the global solution. In fact, MBGO is computationally cheap and easy to construct compare to others method. In this project, two different algorithms are briefly reviewed and applied IEEE 57 bus test case. These algorithms are; Hybrid and Adaptive Meta-model Based Global Optimization (HAM), and Multi-start Space Reduction (MSSR).

**Hybrid and Adaptive Metamodel (HAM)**

Hybrid and Adaptive Metamodel (HAM) is an algorithm that used to solve global optimization problems which was intruded in 2011 by J. Gu et al. HAM has the ability
to improve the search efficiency by automatic selection of the suitable metamodeling techniques during the optimization process. This algorithm uses three different meta modelling methods in the search space to find the global optimization problem with superior performance. These meta modelling methods are include Radial Basis Function (RBF), Response Surface Method (RSM), and Kriging methods. Each of them has unique capability of dealing with particular type of the optimization problems. The main concept of HAM is to start with a hybrid metamodeling scheme and gradually changes the design points sampling scheme into one efficient algorithm. This can be done by self-adapting capability which is automatically selects the three candidates via choosing better sample data points that might be close to the global minimum. Therefore, the sample data adaptive mechanism makes HAM more accurate and efficient global search.

Multi-Start Space Reduction (MSSR)

One of the most recent algorithm that introduced in [19] is Multi-start Space Reduction (MSSR) which is surrogate-based global optimization method. It is considered as black-box method and computationally intensive applications. MSSR works by classifying the design space into three parts; the first one is global space (GS) (original design space), the second one is medium space (MS) which contains the promising region, and the third one is the local space (LS) which is the local area that surrounding the current best solution in the search. For local optimization, MSSR uses a kriging-based multi-start optimization which by sapling selection and exploration the design space. During this process, Latin hypercube sampling is used to establish the staring points and sequential quadratic programming (SQP) is used for the local optimization. By using a new selection strategy, better sample points are obtained to supplement the kriging model, and the estimated mean square error of kriging is used to guide the search of the unknown areas. The multi-start search process is carried out alternately in GS, MS and LS until the global optimum is identified. The method is robust, highly efficient, and full automated. However, since MSSR needs to call the SQP solver many times in each iteration, it may requires more computation time in solving high-dimensional and multi-modal problems.

Due to the complex and multi-modal nature of the DGs design optimization problem introduced in this work. These well-known GO algorithms have been used and the best fitted solution methods have been identified for producing the results of the
grid optimization.
Chapter 3

GENERAL PROBLEM

3.1 Simulation Model and Distribution Network

In this project, the model of distribution network has been simulated in MATLAB using open source package called Matpower. The basic idea of Matpower is to download M-files that can simulate and calculate power flow. Therefore, MATLAB and Matpower are used to carry out the optimal placing and sizing of DGs on IEEE 57-bus test case. The following subsections briefly introduce these software.

3.1.1 Matpower

Matpower is public domain power grid simulation package implemented in MATLAB as M-files that used for solving power flow problems and obtaining optimal power flow. It is an open source simulation tool for researchers and educators that is easy to use and modify. Matpower is designed to give the best performance possible while keeping the code simple to understand and modify. It is able to preform all of the standard of steady-state models for both AC and DC models. The representation of the values of magnitudes are expressed in per unit and radians for angles of complex quantities. Since MATLAB can easily handle the matrices and vectors, all of the models and equations are presented using the capability of matrix and vector form [20].
3.1.2 MATLAB

MATLAB is a high-performance, dynamics system modeling and programming environment that used for technical computing and solving engineering problems. The MATLABs name came from combining the first three letters of two words which are MATrix LABoratory. It was written for projects that carry out matrixes using linear system package (LINPACK) and Eigen system package (EISPACK). Furthermore, it is integrated to become advance programming language and built-in tools for editing, debugging, and visualization which make it excellent for teaching, research, and solving engineering problem. In fact, it was commercially available since 1984, however, nowadays, it becomes one of the essential tool for most universities and industries worldwide. It is worth mentioning that MATLAB has some specific applications come as packages such as optimization, and simulation toolboxes [21].

3.2 Proposed Methods

DGs play important role into any distribution system resulting in enhancement of voltage profile, system reliability, fault currents, and reduction of power losses. As a consequence, if the DGs placed on non-optimal location and size, they will affect the distribution system in negative way such as increasing power losses or affecting voltage magnitude. Therefore, finding the appropriate location and size of DGs will contribute positive affect into the distribution system.

The proposed method is to find the best location and size of DG by installing one or multiple DGs into the distribution system using IEEE 57-bus test case. This can be done by implementing Global Optimization (GO) methods and Metamodel-Based Global optimization methods (MBGO) using MATLAB and Matpower interfaces. Figure 3.1 illustrates the procedure that used to interface MATLAB with Matpower to preform ADN. To find the optimal location of DGs, the algorithm will make random search on all buses except the slack bus which is bus number 1. Once the optimal location is found, the algorithm will incrementally increase the capacity until the power losses is minimized.

In this project, six different cases are investigated and each case has certain number of DGs to obtain the best location and size of the DGs. The total size of DGs should not exceed 300 MW which consider the maximum capacity of the acceptable range.
Genetic Algorithm (GA), Simulated Annealing (SA), Multi-start Space Reduction (MSSR), and Hybrid and Adaptive Meta-model Based Global Optimization (HAM) are used to find the optimal placement and size of the DGs. Each case was run individually by each algorithm and the results are compared to figure out the best performance of the algorithm. Please see Chapter 4 for more details.

Figure 3.1: MATLAB and Matpower interface.

### 3.3 Formulation of Optimal Operation Problem

Minimizing active power losses is the main objective function to determine the optimal location and size of DG’s unit which can be accomplished by the following objective function subject to constrains.

#### 3.3.1 Objective Function

$$ p_{\text{loss}} = \sum_{i,j \in NB} G_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos\theta_{ij}) \quad (3.1) $$

where:
$NB$ is the number of buses.

$V_i$ and $V_j$ are the voltage magnitude at the end buses $i$ and $j$.

$G_{ij}$ is the conductance of transmission line between bus $i$ and $j$.

$\theta_{ij} = \theta_i - \theta_j$ is the phase angle difference between bus $i$ and $j$.

### 3.3.2 Constraints

To meet the demand, we need to balance the generation and demand which can be done via Newton-Raphson power flow method to satisfy power balance by determining the voltage magnitude and angle at each bus by the following equations:

$$\sum_{j=1}^{n} |V_i||V_j|(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) - P_{Gi} + P_{Di} = 0 \quad (3.2)$$

$$\sum_{j=1}^{n} |V_i||V_j|(G_{ij}\sin\theta_{ij} + B_{ij}\cos\theta_{ij}) - Q_{Gi} + Q_{Di} = 0 \quad (3.3)$$

where:

$V_i$ and $V_j$ are the voltage magnitude at the end buses $i$ and $j$.

$G_{ij}$ is the conductance of transmission line between bus $i$ and $j$.

$P_{Gi}$ and $Q_{Gi}$ are the active and reactive output power of the $i$th generator.

$P_{Di}$ and $Q_{Di}$ are the active and reactive output load of the $i$th bus.

$\theta_{ij} = \theta_i - \theta_j$ is the phase angle difference between bus $i$ and $j$.

### Voltage Variation and Generation Capability

$$V_{Gi}^{\min} \leq V_{Gi} \leq V_{Gi}^{\max} \quad i = 1, ..., NG \quad (3.4)$$

### Total Generated Power

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max} \quad i = 1, ..., NG \quad (3.5)$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \quad i = 1, ..., NG \quad (3.6)$$

where:

$V_{Gi}$ generated voltages magnitude of the $i$th bus.

$V_{Gi}^{\max}$ and $V_{Gi}^{\min}$ are the maximum and minimum voltages magnitude of the $i$th bus.

$P_{Gi}$ is the active output power of the $i$th generator.
$P_{Gi}^{max}$ and $P_{Gi}^{min}$ are the maximum and minimum active output power of the $i_{th}$ generator.

$Q_{Gi}$ is the reactive output power of the $i_{th}$ generator.

$Q_{Gi}^{max}$ and $Q_{Gi}^{min}$ are the maximum and minimum reactive output power of the $i_{th}$ generator.

3.4 A Test Example of Distribution Network with DG IEEE-57 Bus

IEEE 57-bus test case is selected for this project to find out the optimal siting and sizing of a single or multiple distributed generations (DGs). This case was established in the early 1960’s by American Electric Power System (AEP) in Midwestern US [22]. The system data is based on 100 MVA and it consists 42 loads totaling 1250.8 MW, 336.4 MVAR. There are seven generators are installed on the system and they are located on buses 1,2,3,6,8,9 and 12 as shown in Figure 3.2.
Based on the results of the base case of IEEE 57-bus, without any modification, the total active and reactive power losses are 27.86 MW, and 121.67 MVAr respectively. The maximum power losses are found on line 1 to 15 by 3.90 MW and 19.96 MVAr. Figure 3.3 illustrates the voltage magnitude for all the buses which clearly indicates bus 31 as lowest magnitude by 0.936 p.u and the maximum magnitude is 1.060 p.u at bus 46.
Figure 3.3: Base case voltage profile.
Chapter 4

Optimal Network Operation under Different Conditions

In this chapter, all the results of each case are presented and discussed in terms of power losses, voltage variation, DG’s location and size, number of function evaluation, and the performance of each algorithm.

The following are the study cases that implemented on IEEE 57-bus:

• Case I: Installing one DG with maximum capacity of 300MW.
• Case II: Installing two DGs with maximum capacity of 150MW each.
• Case III: Installing three DGs with maximum capacity of 100MW each.
• Case IV: Installing four DGs with maximum capacity of 75MW each.
• Case V: Installing five DGs with maximum capacity of 60MW each.
• Case VI: Installing six DGs with maximum capacity of 50MW each.

Each of the above cases is implemented on IEEE 57-bus test case using stochastic (heuristic) global optimization methods and Black-box Based Optimization Algorithms for investigating and comparing the performance of each algorithm. The comparison criteria is based on the minimum of power losses, running time, number of function evaluation, and optimal size of DGs. Two stochastic algorithms are chosen named Genetic Algorithm (GA) and Simulated Annealing (SA), whereas the Black-box methods are used HAM, and MSSE.
4.1 Power Loss Reduction and Voltage Variation

In this project, it has been investigated the behavior of power losses and voltage profile by installing certain number of DGs onto the network, and thus finding the appropriate number of DGs and the optimal associated capacity. The sitting and sizing of a single or multiple DGs are implemented on IEEE 57-bus test case using four different algorithms. The following subsections present some details about each case.

4.1.1 Case I; Installing A Single DG

In case one, a single DG is implemented on IEEE 57-bus test case with maximum capacity of 300 MW and all of the algorithms converged the objective function, which is minimizing the power losses, to 15.9047 MW which about 42.92 % of power loss reduction compare it to the base case. The optimal location is found at bus number 13 and optimal DG’s size is 202.7 MW. Moreover, the voltage profile has been improved compare it to the base case which becomes more stable and its range found between 0.95 and 1.05 pu as illustrated in Figure 4.1.

![Voltage profile](image)

Figure 4.1: Voltage profile pu.

4.1.2 Case II; Installing Two DGs

For the second case, there are two DGs are installed with maximum capacity of 150 MW each. The power losses found is 15.2139 MW which about 45.41 % of power
loss reduction compare it to the base case and 2.5 % compare it to case one. The optimal locations of the DGs are found at buses number 37 and 13 and the optimal DG’s sizes are 70.1887 MW and 150 MW respectively. The total size of the DG’s is 220.18 MW which is about 10 MW bigger than the case one. Moreover, the voltage profile has been improved compare it to the base case as well as case I which becomes more stable and its range found between 0.97 and 1.05 pu as illustrated in Figure 4.2.

![Voltage profile](image)

Figure 4.2: Voltage profile pu.

### 4.1.3 Case III; Installing Three DGs

Regarding the case three where are three units of DGs are installed and each one is capable to generate real power by 100 MW. The power losses found is 16.52 MW which about 40.71 % of power loss reduction compare it to the base case and it worse than case one and two. The optimal locations of the DGs are found at buses number 23, 13, and 30 with optimal DG’s sizes of 66.2028 MW, 96.7644 MW, and 54.8035 respectively. The total size of the DG’s is 217.77 MW which is about 3 MW less than the case two and 7 MW larger than case one. The voltage profile has slight improvement compare it to base case and case one, and its range found between 0.96 and 1.05 pu as illustrated in Figure 4.3.
4.1.4 Case IV; Installing Four DGs

In case four, there are four DGs installed and each one is capable to generate real power by 75 MW. The power losses found is 17.1153 MW which about 38.58% of power loss reduction compare it to the base case. The optimal locations of the DGs are found at buses number 49, 36, 14, and 44 with optimal DG’s sizes of 66.1928 MW, 73.3498 MW, 27.3409 MW and 29.2397 MW respectively. The total size of the DG’s is 196.1232 MW which is less than the cases one to three. The voltage profile has improved compare it to base case and cases one and three, and its range found between 0.97 and 1.05 pu as illustrated in Figure 4.4.
4.1.5 Case V; Installing Five DGs

Regarding the fifth case where are five units of DGs are installed and each one is capable to generate real power by 60 MW. The power losses found is 18.5411 MW which about 38.58 % of power loss reduction compare it to the base case and it is worst case among the previous cases. The optimal locations of the DGs are found at buses number 49, 36, 26, 14, and 31 with optimal DG’s sizes of 57.4417 MW, 50.4852 MW, 14.8424 MW, 27.5575 MW and 40.0154 MW respectively. The total size of the DG’s is 190.3422 MW which is the lowest size among all the cases. The voltage profile has not improved compare other cases, and its range found between 0.95 and 1.05 pu as illustrated in Figure 4.5.

4.1.6 Case VI; Installing Six DGs

Regarding the sixth case where are six units of DGs are installed and each one is capable to generate real power by 50 MW. The power losses found is 13.6439 MW which about 51.03 % of power loss reduction compare it to the base case and it is the best case among of all cases. The optimal locations of the DGs are found at buses number 16, 17, 33, 37, 22, and 53 with optimal DG’s sizes of 44.6897 MW, 46.8786 MW, 9.8500 MW, 43.1085 MW, 48.7238 MW and 26.5109 MW respectively. The total size of the DG’s is 219.7615 MW which is similar to case two. The voltage profile has improved compare other cases, and its range found between 0.97 and 1.05 pu as illustrated in Figure 4.6.
Figure 4.7 summarizes the power losses for all the cases including base case. It can be seen that the minimum power loss is obtained in case six whereas the worst one is case five. Even though the case five has five DGs, its power loss is higher than the others cases which means this case has negative impact on the system. It is worth mentioning that among all the cases, case two and six are the best options of installing DGs into the system. Therefore, the optimal siting and size of DGs is found in case six followed by case two. However, since increasing the number of DGs might have some negative impact such as complexity of controlling the network, installation cost and maintenance, or increasing the chance of short circuit, case two is the best option to minimize the negative impact and power losses.
4.2 Computational Time Comparison

Regarding computational time, it can be observed that the SA and GA are considerably finding the solution faster than HAM and MSSE algorithms. For all of the cases, SA and GA mostly take approximately 10 - 20% of HAM and MSSE to converge as shown in Table 4.1. Since simplicity of the objective function, SA and GA take less time to find the solution, however, HAM and MSSE take more time due to building and generating sample points at each iteration which consume more time to converge.

4.3 Number of Function Evaluation

In terms of the number of function evaluation, there is remarkable difference between the Classic Global Optimization Methods and Metamodel-Based Global Optimization Methods. It can be seen in Table 4.1, the HAM and MSSE are remarkably take 10 - 20% of GA and SA to find the solution. Therefore, Black-box Based optimization are capable and robust to converge with less number of function evaluation.
Table 4.1: Comparison results of each case and algorithm’s performance.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>GA</th>
<th>SA</th>
<th>HAM</th>
<th>MSSE</th>
<th>% of reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I: Installation of 1 DG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU time (sec)</td>
<td>11.7591</td>
<td>10.1555</td>
<td>45.34</td>
<td>50.7400</td>
<td></td>
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<tr>
<td>Power loss (MW)</td>
<td>15.9047</td>
<td>15.9047</td>
<td>15.9047</td>
<td>15.9047</td>
<td>42.92</td>
</tr>
<tr>
<td># of function evaluation</td>
<td>2320</td>
<td>1295</td>
<td>357</td>
<td>281</td>
<td></td>
</tr>
<tr>
<td>Case II: Installation of 2 DGs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU time (sec)</td>
<td>24.2281</td>
<td>9.8738</td>
<td>67.5600</td>
<td>61.3800</td>
<td></td>
</tr>
<tr>
<td>Power loss (MW)</td>
<td>15.2139</td>
<td>15.2157</td>
<td>15.2161</td>
<td>15.2115</td>
<td>45.41</td>
</tr>
<tr>
<td># of function evaluation</td>
<td>6200</td>
<td>2080</td>
<td>391</td>
<td>283</td>
<td></td>
</tr>
<tr>
<td>Case III: Installation of 3 DGs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU time (sec)</td>
<td>35.5263</td>
<td>15.6778</td>
<td>98.1500</td>
<td>69.1700</td>
<td></td>
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<tr>
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<td>8640</td>
<td>3506</td>
<td>382</td>
<td>285</td>
<td></td>
</tr>
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<td>Case IV: Installation of 4 DGs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU time (sec)</td>
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<td>75.1384</td>
<td>135.9700</td>
<td>71.4300</td>
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<tr>
<td>Power loss (MW)</td>
<td>17.1197</td>
<td>17.1153</td>
<td>17.1125</td>
<td>17.1161</td>
<td>38.58</td>
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<tr>
<td># of function evaluation</td>
<td>2960</td>
<td>17903</td>
<td>412</td>
<td>287</td>
<td></td>
</tr>
<tr>
<td>Case V: Installation of 5 DGs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU time (sec)</td>
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<td>26.6520</td>
<td>161.3800</td>
<td>73.0200</td>
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<tr>
<td>Power loss (MW)</td>
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<td>18.5358</td>
<td>18.5416</td>
<td>18.5352</td>
<td>33.47</td>
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<td>3200</td>
<td>6142</td>
<td>413</td>
<td>289</td>
<td></td>
</tr>
<tr>
<td>Case VI: Installation of 6 DGs</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPU time (sec)</td>
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<td>98.4000</td>
<td></td>
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<tr>
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<td>13.6439</td>
<td>13.6536</td>
<td>13.6673</td>
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<tr>
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<td>10024</td>
<td>414</td>
<td>291</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 5

Summary

5.1 Summary of this Work

Distributed generations (DGs) are considered as an important tool in the power distribution system (PD) of a Smart Grid. The design optimization of DS is studied in this project. The research is aimed at to produce the optimal DS design with optimal sitting and size of DGs in the network to best utilize the renewable energy sources, and to ensure smooth and reliable power flow to meet customer’s power demand using a robust network design. In this project, a method for identifying the optimal location and size of DGs through network optimization is introduced and tested using the IEEE 57-bus power distribution system test case. After reviews on the background of Smart Grid and DG technologies and advanced global optimization search algorithms, formulation and solution method of the optimization problem have been introduced.

The type-p distributed generator, which is only capable of supplying real power to the system, is considered in this project. Six cases have been studied, each of which contains certain number DGs with different sizes. The power network modeling, simulation and optimization have been done using MATLAB and MatPower tools. Four different GO algorithms have been tested to identify the best GO tools for handling this type of design optimization problem. The introduced approach showed improved network designs with better network performance, and accomplished computation method.
5.2 Future Work

Future research on this subject may consists of using other types of DG to form the best combination of DGs in the DS of a smart grid; to perform simulation on daily operation to ensure the routine optimal operation of active distribution networks; and to apply the new method to bigger and more complex power networks.
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