ADDIS ABABA SCIENCE AND TECHNOLOGY UNIVERSITY

ASSESSMENT AND IMPROVEMENT OF VOLTAGE STABILITY WITH COORDINATED CONTROL OF HARMONIC DISTORTION USING OPTIMAL PLACED DISTRIBUTED GENERATION UNIT

MASTER'S THESIS

By

EBE MEKONEN TAREKE

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

COLLEGE OF ELECTRICAL AND MECHANICAL ENGINEERING

FEBRUARY 2022

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Advisor: TESHOME GOA (Ph.D.)

A Thesis submitted as a Partial Fulfillment to the Requirements for the Award of the Degree of Master of Science in Electrical and Computer Engineering

(Power Engineering)

to

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

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FEBRUARY 2022

DECLARATION

I hereby declare that this thesis entitled "**Assessment and Improvement of Voltage Stability with Coordinated Control of Harmonic Distortion Using Optimal Placed Distributed Generation Unit**" was prepared by me, with the guidance of my advisor. The work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted, in whole or in part, for any other degree or professional qualification.

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APPROVAL PAGE

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ABSTRACT

Voltage stability problem results significant challenge in distribution networks. Voltage stability can be improved using optimal placed distributed generation (DG) in distribution networks. However, the installation of inverter-based DG can increase level of harmonics, which could exceed the permissible harmonic distortion level. This paper presents the voltage stability improvement with coordinated control of harmonic distortion using particle swarm optimization (PSO) based optimal placed DG unit. The PSO, which is developed based on achieving the multi-objective functions, voltage stability index (VSI) improvement and active power loss reduction subjected to different constraints. The parameters voltage profile and VSI are determined by backward forward sweep method, and harmonics are determined by using the harmonic power flow approach. The proposed methodology is tested in 78-bus radial distribution network of the case study and in the standard IEEE-69 bus radial distribution network. The integration of type 1, 2 and type 3 DG units interims of bus voltage profiles, VSI and power loss are compared. The minimum voltage profile is improved 6.19%, 4.07%, and 6.8% in case of type 1, type 2, and type 3 DG units respectively, and the minimum VSI is also improved 27.39%, 17.3%, and 30.3% in case of type 1, type 2, and type 3 DG units respectively on the 78-bus network. The result of placing DG units on the 78-bus and IEEE-69 bus radial distribution network shows that the improvement in bus voltage profile, VSI, and reduction in power loss. Similarly, the result shows that the average voltage total harmonic distortion (THDv) is controlled within the standard IEEE-519 acceptable limit for the radial distribution systems based on the optimal sized and controlled DG units. Finally, the overall result reveals that designing and placing DG unit for optimal identified bus improves both voltage stability and system power transfer capacity.

Keywords: *Distributed Generation (DG), Harmonic Power Flow (HPF), Particle Swarm Optimization (PSO), Voltage Stability Index (VSI)*

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LIST OF ABBREVIATIONS AND SYMBOLS

BCBV	Branch Current to Bus Voltage
BIBC	Bus Injection to Branch Current
DG	Distributed Generation
DLF	Distribution Load Flow
EEU	Ethiopian Electric Utility
FACTs	Flexible Alternating Current Transmission
GA	Genetic Algorithm
HPF	Harmonic Power Flow
LSI	Loss Sensitivity Index
PoVC	Point of Voltage Collapse
PSO	Particle Swarm Optimization
P-V	Active Power-Voltage
Q-V	Reactive Power-Voltage
SA	Simulated Annealing
AI	Artificial Intelligence
THD	Total Harmonic Distortion
THDv	Voltage Total Harmonic Distortion
Var	Volt-Ampere Reactive
VSI	Voltage Stability Index
B/F	Backward Forward
GMR	Geometric Mean Ratio
SCADA	Supervisory Control and Data Acquisition
IEEE	International Electrical and Electronic Engineering
A	Relationship between Harmonic Branch Current and Harmonic Bus Current
HA	Relationship between Harmonic Bus Voltage and Harmonic Bus Current
$f1$	Total Active Power Loss
$f2$	Inverted Total Voltage Stability Index
D	Distance between Two Conductors

CHAPTER ONE
INTRODUCTION

1.1 Background

Voltage stability issues have gained significant attention since recent years due to occurs of voltage collapse. In a system voltage stability problem occurs because of a sudden large disturbance, increase in demand, and loss of generating units, loss of transmission lines, and progressive decline or rise in voltage level caused by various means [1]. The power system network has generation, transmission, and distribution stages which must be properly maintained to keep the specified voltage and frequency level of the system. Voltage level is maintained within a specified range traditionally using on-load tap changers and FACTs devices [2]. Voltage stability is one of the requirements for the steady operation of distribution networks. Connection of distributed generation (DG) into the distribution system may contribute to harmonic distortion in the system, which is depend on the type of DG units and the power converter technology. In this paper THDv arises due to the installation of DG units is used as constraint of the proposed objective function in order to control the harmonic impact.

Unlike traditional based optimization techniques such as sensitivity factor, optimal power flow, and repetitive load flows, the artificial intelligent (AI) methods work well for complex optimization problems such as DG placement problem. The AI methods that are used to apply for placement and sizing of DG units includes particle swarm optimization [3], genetic algorithm [4], bacteria foraging algorithm [5], tabu search, differential evolution algorithm [6], and ant colony algorithm [7]. In this thesis, Particle Swarm Optimization (PSO) is used for optimal placement and size of DG unit with the help of MATLAB program. The objective of the DG placement is to reduce the total active power losses and improve the voltage stability of the system with the constraint of THDv so as to control the harmonic impact of the DG unit. Case study is carried out in Addis west distribution substation which is found in Addis Ababa city around Kolfe Keranio Sub-City Woreda 10, because of this substation has highest number of feeders which are long distanced and overloaded, and hence prone for voltage instability and high power loss [8,9]. The substation has three 132kV incoming lines and twelve 15kV outgoing lines, and it contains two 50MVA 132kV/15kV transformers. The twelve outgoing feeders in the substation are K01, K02, K03, K04, K05, K06, K10, K11, K12, K13, K14, and K15 as shown in Figure 1.1 below. For the study of this thesis Line-12 K01 feeder line is taken, since this feeder is loaded more, long distanced line.

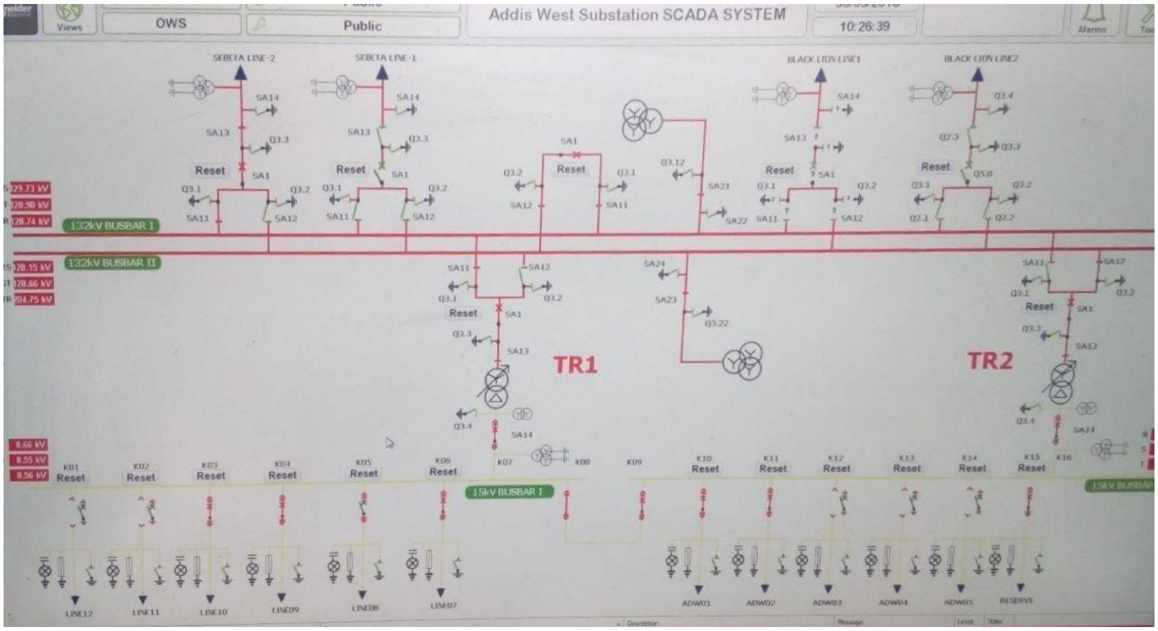

Figure 1.1: SCADA system of Addis West Substation [9].

1.2 Statement of the Problem

Voltage stability problem is one of the challenging problem due to the strengthening of power system by various means. Another challenging problem of power system is harmonic distortion in the system due to widespread use of power electronic devices. The growth in consumptions and high power loss in distribution system resulted to operate close to the power capacity limit of the system. Furthermore, the need to lower carbon emissions DG is promoted due to decrease fossil fuels consumption and the difficulty to construct new lines and power plants because of the geographical and environmental concerns. Improper placement and sizing of distributed generators may reduce the positive impacts gained from the DG integration with the dominant negative impacts. In response to these challenges, this thesis work intends to determine the impact of DG integration on network technical parameters by conceiving the proper placement and size of DG units considering their harmonic impact.

1.3 Significance of the Study

This thesis might use as a reference and may provide a foundation for further research on similar areas of study by other researchers. Finally, the results of this thesis serve as a base for distribution generator planners and designers and give an idea about the distribution generation. Hence, optimal placing and sizing of DGs have a significant role for the local distribution company as well as the end users such as: power loss reduction, voltage profile enhancement, and voltage stability improvement, maintaining the voltage regulation and harmonic distortion with the permissible limits, DGs such as grid-free renewable may be particularly suitable for remote areas.

1.4 Objective of the Study

1.4.1 General Objectives

The main goal of this thesis work is to improve voltage stability of distribution network with proper insertion of distributed generation unit considering their harmonic impact.

1.4.2 Specific Objectives

Basically this paper deals on:

- Formulate an objective function based on total active power loss and VSI for the optimization problem with the constraint of THDv.
- Make voltage stability assessments on the proposed network, and perform backward forward sweep and harmonic power flow analysis.
- Identify both the optimal place and size of DG unit for voltage stability improvement using the PSO optimization technique.

1.5 Scope of the Study

- The allocation and size of the DGs are considering only the active power loss, voltage stability and THDv arises from DG unit installation.
- Only THDv arises due to DG unit installation is discussed as harmonic impact of the system detail harmonic assessment and mitigation is beyond this study.
- No practical implementation as they all are done by using MATLAB simulation software.

1.6 Organizations of the Study

This thesis has five chapters and appendixes and it is organized as follows: Chapter two contains theoretical background overview of distribution system, discusses about distribution voltage stability, distribution generation, highlights about harmonic distortion and finally reviews literatures. Chapter three describes the proposed methodology and the modeling. Chapter four contains the results and analysis tested on local 78-bus and standard 69-bus radial distribution Systems. Chapter five presents conclusions and recommendations for future research work.

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Overview of Distribution System

Distribution systems is the link used to transfer electric energy from the distribution substation to the end users. Typical it begins about 30kV to 60kV three phase medium voltage and terminate at a lower secondary three phase and/or single phase voltage typically below 1kV [10].

2.1.1 Power Loss

Highest technical and non-technical losses happens in the distribution system [11]-[13]. Technical losses in power system are due to current flowing through the internal electrical resistance of transmission lines and transformers of the power system networks. Technical losses are losses such as: copper losses, dielectric losses, and induction and radiation losses**.** Measures should be taken for reducing technical losses are:

- ✓ Identification and improving of the weakest areas in the distribution system.
- ✓ Installation of DG units for power loss reduction.
- ✓ Shunt capacitors insertion for power factor improvement.

Non-technical losses are caused due to actions external to the power system, such as theft, metering inaccuracies and unmetered energy [14].

2.2 Voltage Stability in Distribution System

2.2.1 Power System Stability

The capability of power system to recover steady state operation after being subjected to a physical disturbance can be termed as power system stability [15]. Power system stability can be classified as rotor angle stability, frequency stability, and voltage stability, [16].

2.2.1.1 Rotor Angle Stability

Rotor angle stability is the ability of interconnected synchronous machines of a power system to remain in synchronism. Rotor angle stability is associated with the balance between the mechanical torque of the generating unit's turbine and the electromagnetic torque of its generator [15].

2.2.1.2 Frequency Stability

Frequency stability refers to the ability of the power system to maintain the system frequency within acceptable limits under normal operation or following a system disturbance. The condition to keep the nominal frequency is keeping the equilibrium between the active power generated, and the sum of the power absorbed by the loads and the system's active power losses [16].

2.2.1.3 Voltage Stability

The capability of a power system to maintain steady acceptable voltages at all buses of the system under normal operating conditions and after being exposed to a disturbance is termed as voltage stability [15]. Usually voltage stability is analyzed using P-V curves, Q-V curves, stability indices, modal and sensitivity analysis. However, these techniques are time-consuming and need considerable computation effort [17]. Due to the complexity and being large the distribution networks different indices have been developed by researchers, hence a comprehensive review of voltage stability indices has been done in [18]. The voltage stability index (VSI) presented in [19] was used in this work as the objective function together with active power loss. Voltage instability is not only due to progressive decline in bus voltages but also due to progressive rises in bus voltage also exists which is caused by the capacitive behavior of a network. Total or partial voltage collapse occurred if the post disturbance equilibrium voltages are below the acceptable limits [20]. DG, capacitors, FACTs devices, and load shedding, and so on can be used to mitigate voltage stability problem in the system.

2.3 Distributed Generation

Distributed generation can be defined as an electric energy sources connected directly to the distribution network, usually via power electronic devices, which is located near the electric loads to be supported [21, 22]. DG units can be classified based on output power capacity as micro, small, medium, and large distributed generation. DG units can be also classified interims of interfacing devices to the grid, as inverter based DG units, such as PV systems, wind turbine generators, fuel cells, and micro turbines, and non-converter based DGs, like mini hydro synchronous generators and induction generators [23]. DG can be also classified into four major types based on their terminal characteristics in terms of real and reactive power delivering capability [24, 25] as follows:

- Type 1 DGs: those inject real power only in to the system, DGs such as photovoltaic, micro turbines, fuel cells are categorize as type 1 , and are integrated to the main grid with the help of converters/inverters.
- Type 2 DGs: DGs which are injecting reactive power only into the grid such as synchronous compensators.
- Type 3 DGs: those injecting both real and reactive powers in the grid, synchronous machine cogeneration, gas turbine, etc. are good examples of type 3 DGs.
- Type 4 DGs: those which are injecting real power but consuming reactive power, like induction generators that used in wind farms.

DGs based on type of technology used in the power generation are wind turbines, micro turbines, photovoltaic systems, fuel cells, energy storage, and synchronous generator etc. [26].

2.3.1 Advantage and Drawback of DG Units

2.3.1.1 Advantage of DG Units

Using DG units in power system has technical and economic benefits [27]. Some of the major technical benefits are reduce line losses, improve voltage profile and voltage stability, reduce emissions of pollutants, enhanced system reliability and security, and improved power quality.

2.3.1.2 Drawback of DG Units

Some of side effects of installation of DGs to the existing distribution system are listed below [28].

- Injection of harmonics to the system due to power electronic devices which are used to connect DG units with the grid.
- DG unit might cause over voltage, fluctuation in voltage, and also may increase the power loss in the distribution system when fails properly integration.

2.3.2 Impact of DG Units on Voltage Stability

Since DG units provide power closely to the loads, and hence the distribution line losses are significantly reduced, which is resulted in reducing voltage drop in the system.

$$P_r = |V_r||I_r|cos\theta_r \quad (2.1)$$

$$Q_r = |V_r||I_r|sin\theta_r \quad (2.2)$$

Where, P_r is active power, Q_r is reactive power, V_r is voltage magnitude, I_r are the current flowing, and $\theta_r\ is$ the angle difference between V_r and I_r.

To drive the relationship between Q_r and voltage drop ($\Delta V = |V_s| - |V_r|$) Consider V_r as the reference voltage i.e. $V_r = |V_r| < 0$ and $V_s = |V_s| < \delta,$

$$P_r = \frac{|V_r||V_s|}{X} sin\theta_r \quad (2.3)$$

$$Q_r = \frac{|V_r||V_s|}{X} cos\theta_r - \frac{|V_r|^2}{X} \quad (2.4)$$

Considering δ too small, then cosδ ~1, and hence equation (2.4) becomes as follows:

$$Q_r = \frac{|V_r|}{X}(|V_s| - |V_r|) \quad (2.5)$$

It can be seen that from equation (2.5) Q is directly proportional to the magnitude of voltage drop in the system. Even though, integration of type 2 DG units those injecting reactive power can influence the voltage stability directly by injecting reactive power to the system, integrating of type 1 DG units such as PV Solar and Wind have significant effect not only to the voltage stability but also to voltage profile and power loss of the system.

2.3.3 Harmonic Impact of DG Units

Usually, DG units integrate in to the grid with help of power electronics interface equipment, which may inject harmonics in to the system. An integer multiple of the fundamental frequency of the system are termed as harmonics. Harmonics in the electrical power system produce unwanted disturbing effects in the system. Power electronic devices such as IGBT, diodes, thyristhors and the like non-linear loads are used in the converter station [29].

2.3.3.1 Harmonic Source Modeling

Harmonic distortion causes severe damage in electrical networks such as lowering power factor, overheating, incorrect operation of protective relays, and so on [30]-[32]. Based on the recommended value of IEEE-519 standard THD should be equal or less than 5% [33]. Thyristor drives, rotating machines, transformers and DG units are major sources of harmonics. Full-wave rectifiers used in conversion of AC to DC inject harmonic currents in to the system. The harmonic number can be given by the equation (2.6).

$$h = np \pm 1 \tag{2.6}$$

where: h=harmonic order,

n=an integer 1, 2, 3…,

p=number of current pulses per cycle

Thus, the harmonic order that will be present in a 3-phase 6-pulse rectifier, are 5, 7, 11, 13, 17, 19, and so on. Since the percentage of harmonics per harmonic order present in the system decrease with increasing the harmonic number h, the harmonic current injected at critical buses can be calculated as the reciprocal of the harmonic number as shown in equation (2.7), and then multiply with the fundamental frequency [34].

$$I = 1/h \tag{2.7}$$

It can be said that the non-inverter based DGs are linear loads, produce no harmonics, while inverter-based DGs are nonlinear loads that inject harmonic currents into the system, a linear DG unit admittance can be modeled as a series combination of a resistance and an inductive reactance as given in equation (2.8) [35].

$$Y_{dg,i}^{(h)} = \frac{1}{\sqrt{h}R_{dg,i} + jhX''_{dg,i}} \tag{2.8}$$

Where $R_{dg,i}$ and $X''_{dg,i}$ are the resistance and sub transient reactance of generator i, respectively.

Harmonic current sources were injected to the system at the critical buses to demonstrate the harmonic effect. The amplitude and angle of the injected harmonic current [36] is given in equation (2.9).

$$I(h)=\frac{1}{h*\sin(hwt)} \quad (2.9)$$

where, $w=2\pi f$,

f = fundamental frequency of the system,

h= harmonic number

For this study the harmonics sources are calculated using equation (2.7) for the harmonic orders of 5^{th}, 7^{th}, 11^{th}, 13^{th} and 17^{th} and inserted in the critical buses. Moreover, harmonic power flow (HPF) which is based on backward/forward sweep method is utilized to calculate the harmonic load flow solution, and hence the average voltage total harmonic distortion (THDv) is calculated.

2.4 Optimization Techniques

Suitable placement of DGs in power system is required due to cost and their side effect minimization. Many authors use different optimization techniques for placement of DG units in distribution networks, some of them widely used are genetic algorithm (GA), simulated annealing (SA), differential evolution (DE), and particle swarm optimization (PSO).

PSO was used in this thesis work due to its several advantages like robustness, efficiency, simplicity, and computational effort. When compared with other Optimization technique algorithms it has been found that PSO requires less time to converge and hence suit for complex problems like DG placement and sizing [37].

Table 2.1: Comparison of GA, SA, DE, and PSO optimization techniques.

Optimization technique	Parameters	Performance	Advantages	Disadvantages
GA	Reproduction, Crossover, Mutation.	Find the best among the other.	Essay to understand, Supports multi-objective function, Work well on mixed discrete and continuous problem.	Implementation is still complex, Computational expensive, Time consuming.
SA	Initial temperature, Cool down factor.	Heating a material and then slowly lowering the temperature.	Useful in finding global optima in the presence of large numbers of local optima, Implementation it's pretty simple.	Single solution based algorithm, Very slow algorithm to converge.
DE	Population size, Differential weight, Crossover, Generation number.	Optimizes problem by iteratively improving a candidate solution based on an evolutionary process.	Handle nonlinear and non-differentiable objective functions, Flexibility of the procedures, Using combination of the same population chromosome in forming new generation.	Weak exploitation capability, Probably none of previous generation chromosomes are carried forward to the next generation.
PSO	Current position, Current velocity, Personal best, Global best.	Reach target with minimum duration.	Simple concept, Easy implementation, Robustness to control parameters, Computational efficiency.	It is easy to fall into local optimum in high-dimensional space, Too much dependent on global best.

2.4.1 Particle Swarm Optimization Technique

PSO was introduced by Kennedy and Eberhart in 1995 [38] which was inspired by model of the social behavior of bird flocking or fish schooling. Each particle that is each bird has a position and velocity associated with it. In order to get seed food/optimized needed parameter particles change their position by adjusting their velocity, and each particle memorize the best location identified and communicate the information of the best location each other. Velocity of the particles are modified using flying experience of the particular particle and the entire group. Different variants of the PSO algorithm were introduced, however the most standard one is introduced by Andries and P. Egelbertch in [39]. PSO has only two equations, which makes it's good feature is simplicity.

2.5 Review of Literatures

Different literatures conducted integrating of DG units into distribution systems using different objective functions and optimization techniques.

The author in [4] offered a multiple objectives like reduction of real power losses and voltage deviation at the point of integration of type 1 DGs using VSI, based on GA, and was tested on standard IEEE-69 radial distribution test systems. In [41] also proposed a multi DG placement and sizing for distribution systems which was based on a VSI using several types of PSO optimization algorithm, and was tested on 12-bus and 69-bus radial distribution networks. Another author in [42] dealt with the optimal placement of different type of DG units in distribution networks based on voltage stability maximization and minimization of power losses using bat algorithm optimization technique. Injection of P, Q, and injection of both powers together have been applied, and tested on the standard 33, 69 buses test feeders, but failed to consider DG units effect interims of harmonics.

Research paper in [43] discussed on optimal planning of distributed generation for improved voltage stability and loss reduction with fuzzy logic and new analytical method on 12-bus, 33-bus and 69-bus radial distribution. In [44] demonstrated the reduction of THD and the system losses using the backward/forward sweep method for optimal site and size of DGS. BIBC and BCBV matrices are calculated to perform load flow analysis and harmonic flow analysis in distributed system on IEEE 33 bus radial system. Forward-backward power flow with respect to a VSI was discussed in [45] for optimal size and location of DG units on the 34-bus IEEE standard network. Even if, THD, VSI, and power loss were discussed in general, but did not say how specifically DG units contributes for those parameters.

DG units sizing was formulated in [46] using PSO with an objective function of improving the voltage stability, and testing on standard IEEE 33 bus and 69 bus distribution systems. In [47] presented optimal sizing and location of DG units for losses minimization and voltage stability improvements with the help of student version of the AMPL software. In [48] applied optimal DG placement for reduction of power losses and voltage profile enhancement of a distribution system using PSO on the IEEE 30 bus and 33 bus radial distribution systems. Paper in [49] discussed multi objective function based on minimization of real power losses and THD, and improve the system's voltage profile using PSO for DG sizing on the IEEE 15-bus system. In the above reviewed literatures most researchers have developed voltage stability indices to analysis voltage stability in different electrical networks. It also observed that different objective function, different method of optimization technique and test network was used to locate and size of distribution generation technologies. But most researchers did not consider the effect of DG units interims of harmonic impact, therefore this paper the average voltage total harmonic distortion (THDv) is used as constraint of the objective function to control the harmonic impact of DG units.

CHAPTER THREE
METHODOLOGY

3.1 Data Collection and System Modeling

One of the artificial intelligence techniques called particle swarm optimization is used in this research work due to its fast converging ability to find optimal place and/or size of DG units with the help of MATLAB program. The requirement data for the study have been collected from Ethiopian Electric Utility (EEU) the district of Addis West electrical distribution substation. After power flow analysis is done, voltage profile, voltage stability index and the amount of lost power is determined. This thesis work has proposed a solution for the placement and sizing of DG units to reduce power losses and improve voltage stability in Addis West distribution system and standard IEEE-69 bus radial distribution network.

3.1.1 Network Introduction

The steady state diagrams of the proposed network is given in Appendix I, and it consists 78 buses and 77 branches, 15kV and 110MVA are considered as base values, the bus data and line data of the network is given in Appendix II Table A.10.

3.1.2 System Modeling

3.1.2.1 Impedance Calculation of the Network

The impedance of branches of the proposed networks is calculated at 50Hz fundamental frequency, per one kilometer length, and are given in equation (3.1) below.

$$Za = Ra + j0.06832 \ln\frac{D}{GMRa}\ \Omega/\text{km} \quad (3.1)$$

$$D = \sqrt[3]{Dab * Dbc * Dac} \quad (3.2)$$

Where, Za, Ra (in Ω /km): impedance and resistance of line conductor a of the network respectively. D(in m): distance between line conductors of the network. Dab, Dbc, Dac (in m): distance between, a and b, b and c, and a and c line conductors of the network respectively.

GMR for standard conductors is given by equation (3.3).

$$GMRa=K*r \tag{3.3}$$

where, GMRa: geometric mean ratio of line conductor a of the network,

K: GMR factor,

r: actual radius of line conductor of the network.

Using Appendix II Table A.11 and Table A.12. Applying equation (3.1) the impedance of the network are calculated as follows. For AAC-120 conductor type, is given by:

$$Za=Ra+j0.06832\ln\frac{D}{GMRa}\,\Omega/\text{km}$$

$$Za=0.2853+j0.06832\ln\frac{0.72135}{0.00924}\,\Omega/\text{km}$$

$$Za=0.2853+j0.2738\,\Omega/\text{km}$$

For 3-phase, 3-conductors their respective impedances are equal: Za= Zb= Zc

Similarly applying equation (3.1) the impedance of the network, for AAC-95 conductor type (D=0.72135 and GMRa= 0.004129), for AAC-50 conductor type (D=0.72135 and GMRa=0.00288), and for AAC-25 conductor type (D=0.72135 and GMRa=0.001881) can be calculated.

The shunt admittance of overhead lines is neglected since the line is short.

3.1.3 IEEE-69 Bus Radial Distribution System Modeling

This standard test system has 69 buses and 68 branches, the total real and reactive power demand is 3.7905 MW and 2.6941 MVar, respectively, its line and bus data are given in Appendix IV Table A. 13 [50].

3.2 Distributed Generation Sizing and Placement

3.2.1 Problem Formulation

The proposed method aims to reduce active power loss, and improve the system voltage stability index through the following objective functions.

$$F_{min} = w_1 f_1 + w_2 f_2 \tag{3.4}$$

Where f_1 represents the total active power loss, and f_2 represents inverted total voltage stability index, while w_1 and w_2 are the weighting factors, which are usually considered as follows: $w_1+w_2=1$ $0\leq w_k \leq 1$

Power Losses: The total real power losses at all nodes cause by circulating current in the network by substation and DGs are calculated. The total real power loss is defined by:

$$f_1=Ploss = \sum_{i=1}^{n} Plossi \quad (3.5)$$

where, $Plossi=RI^2$,

n is the number of lines and i=1,2……n,

R= line resistance between to buses,

I=line current.

Total Harmonic Distortion (THD) of the system should be controlled and therefore it is used as constraint of the objective function in this paper. The average voltage total harmonic distortion (THDv) is defined by equation (3.6).

$$\text{THDv}=\frac{\sum_{i=1}^{m} THDvi}{m} \quad (3.6)$$

where, $\text{THDvi}=\sqrt{\frac{\sum_{h=5}^{hmax} |V_i^h|^2}{|V_i^1|^2}}$,

m is the number of buses,

h=5, 7, 11…..hmax (hmax=17)

$|V_i^h|$=h-th harmonic bus voltage at bus i,

$|V_i^1|$=fundamental bus voltage at bus i.

Voltage Stability Index (VSI): it is introduced by Charkravorty and Das [19] to identify sensitive buses to voltage collapse. Those buses far away from the substation are subject to more voltage drop and hence, sensitive to voltage collapse. The aim here is to make the value of VSI as far as possible from zero since zero value for VSI represent voltage collapse in the system.

$$f_2 =1/\sum_{i=1}^{n} VSIi \quad (3.7)$$

where, n is the number of lines and i=1,2……n.

To derive VSI equation in radial distribution systems, consider simple radial distribution network below.

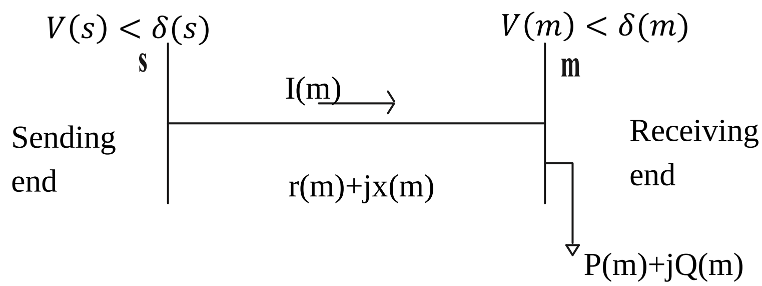

Figure 3.2: Simple distribution network diagram

where, V(s)= Voltage at sending bus,

V(m)= Voltage at receiving bus,

Q(m)= Reactive power at receiving bus,

P(m)= Active power at receiving bus,

r(m)= Resistance of branch sm,

x(m)= Reactance of branch sm.

$$I(m)=\frac{V(s)<\delta(s)-V(m)<\delta(m)}{r(m)+jx(m)} \tag{3.8}$$

$$P(m)+jQ(m)=V^{*}(m)I(m) \tag{3.9}$$

Using equation (3.8) and equation (3.9) we have

$$|V(s)|^{4}-4|V(s)|^{2}(r(m)P(m)+x(m)Q(m))-4(x(m)P(m)-r(m)Q(m))^{2}=0 \tag{3.10}$$

$$\text{Let } b(m)=|V(s)|^{2}-2P(m)r(m)-2Q(m)x(m)\,,\ c(m)=(P^{2}+Q^{2}(m))(r^{2}+x^{2}(m)) \tag{3.11}$$

Substituting equation (3.11) in equation (3.10) to get equation (3.12).

$$|V(s)|^{4}+b(m)\,|V(s)|^{2}+c(m)=0 \tag{3.12}$$

From equation (3.12) the condition for load flow convergence in radial distribution system is given in equation (3.13) below.

$$b(m)^{2}-4c(m)\geq 0 \tag{3.13}$$

By substituting equation (3.11) in equation (3.13) after simplification the VSI equation at i-th bus is given by equation (3.14).

$$VSI_i = |V(s)|^4 - 4|V(s)|^2 (r(m)P(m) + x(m)Q(m)) - 4(x(m)P(m) - r(m)Q(m))^2 \quad (3.14)$$

For stable operation of radial distribution systems, $VSI(m) \geq 0$, for m=2,3……NB

Then finally, the overall system voltage stability can be evaluated as follows,

$$VSI = \sum_{m=2}^{NB} VSI(m) \quad (3.15)$$

The objective function for the distribution power loss reduction and voltage stability enhancement considering DG unit is subjected to the following constraints:

Bus voltage constraint

$$V_{min} \leq |V_i| \leq V_{max}, \quad (3.16)$$

where, Vmin is the lower bound of bus voltage limit,

Vmax is the upper bound of the voltage limit,

|Vi| is the root mean square value of the i-th bus voltage. In this paper Vmin=0.95p.u and Vmax=1.05p.u is used.

Total harmonic distortion constraint

$$THD_{vi}(\%) \leq THD_{v,max} \quad (3.17)$$

where THDv,max is the maximum allowable level at each bus i.e. 5% from IEEE-519.

DG unit power rating constraint

To avoid voltage rise problem on the system, DG sizes should be below the total load of the system [21]. DG_{Pmin} and DG_{Qmin} are the minimum active and reactive power of DG units respectively and are set zero, and DG_{Pmax} and DG_{Qmax} are the maximum active and reactive power of DG units respectively, and are set as 90 % of the total active and reactive power load on the system respectively.

$$DG_{Pmin} \leq DG_P \leq DG_{Pmin} \quad (3.18)$$

$$DG_{Qmin} \leq DG_Q \leq DG_{Qmin} \quad (3.19)$$

where DG_P and DG_Q are active and reactive power DG units size.

3.2.2 Loss Sensitivity Index (LSI)

In this thesis work, the candidate buses are selected by the loss sensitivity index techniques with active power loss. This methodology is formulated to allocate DGs by differentiating the power losses equation of the nodes that helps to identify the candidate buses. Consider a simple radial distribution line with impedance R_k+jX_k and a load of $P_{i+1}+jQ_{i+1}$ connected between 'i' and 'i+1' bus is shown in Figure 3.3.

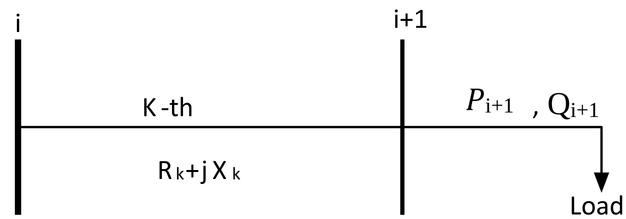

Figure 3.3: A distribution line between buses i and i+1 representation

Computation of real power loss in the branch 'k' is given by $I_k^2*R_k$, and the simple distribution network as shown in Figure 3.3 can be formulated as;

$$\text{Ploss (k)} = R_k \frac{P_{i+1}^2+Q_{i+1}^2}{V_{i+1}^2} \tag{3.20}$$

In the same principle, the reactive power loss in branch 'k' between 'i' and 'i+1', similarly the reactive power loss at branches can be expressed as;

$$\text{Qloss (k)} = X_k \frac{P_{i+1}^2+Q_{i+1}^2}{V_{i+1}^2} \tag{3.21}$$

where: P_{i+1} is total active power supplied at bus 'i+1'.

Q_{i+1} is total reactive power supplied at bus 'i+1'.

V_{i+1} is voltage at bus 'i+1'.

R_k, X_k are the resistance and reactance of the branch 'k' respectively.

LSI can be derived using the differential of the Ploss (k) with respect to V_{i+1} while, P_{i+1}, Q_{i+1} and R_k are kept constant as shown in equation (3.22) below.

$$LSI(k) = \frac{\partial Ploss(k)}{\partial V_{i+1}} = \frac{-2*R_k*(P_{i+1}^2+Q_{i+1}^2)}{V_{i+1}^3} \tag{3.22}$$

Those buses with highest positive value of LSI are considered as candidate bus for DG unit installation, in order to increase the probability of the optimal DGs placement.

3.3 Load Flow Analysis

Load flow is used for analyzing electrical network performance, it solves non-linear problems iteratively, among methods most used are backward/forwards sweep method, Gauss-Siedel, Newton-Raphson, and fast decoupled methods. Since the high R/X nature of radial distribution networks which causes problems in the convergence of conventional load flow algorithms, the backward/forwards sweep method is used in this research paper due to the convergence ability of this algorithm.

3.3.1 Backward Forwards Sweeping Method

Backward/forward sweep power flow algorithm was developed by Teng [51]. Two matrices are calculated from structure of distribution network, which are termed as BIBC and BCBV.

3.3.1.1 Algorithm for Forward Backward Sweep Load Flow

In this algorithm, the equivalent current injections, the bus-injection to the branch current matrix (BIBC) and the branch-current to the bus-voltage matrix (BCBV) are utilized. For bus-i, the complex load S_i is expressed as,

$$S_i = P_i + jQ_i \quad (3.23)$$

where; i = 1, 2, 3... N

From the specified complex power S_i at bus-i which is expressed in equation (3.23). From equation 3.23, the equivalent current injection is expressed in equation (3.24).

$$I_i = \left(\frac{P_i + jQ_i}{V_i}\right)* \quad (3.24)$$

For the load flow solution, the equivalent current injection at the k-th iteration at the i-th node is expressed as;

$$I_i^k = \left(\frac{P_i^k + jQ_i^k}{V_i^k}\right)* \quad (3.25)$$

where, , P_i, and Q_i are complex power, real power, and reactive power at the i-th bus respectively,

$V_i{}^k$, $I_i{}^k$ are the bus voltage, and the equivalent current injection at the k-th iteration for i-th bus respectively,

P_i^k, Q_i^k are the real part and the imaginary part of the equivalent current injection at the k-th iteration for i-th bus respectively.

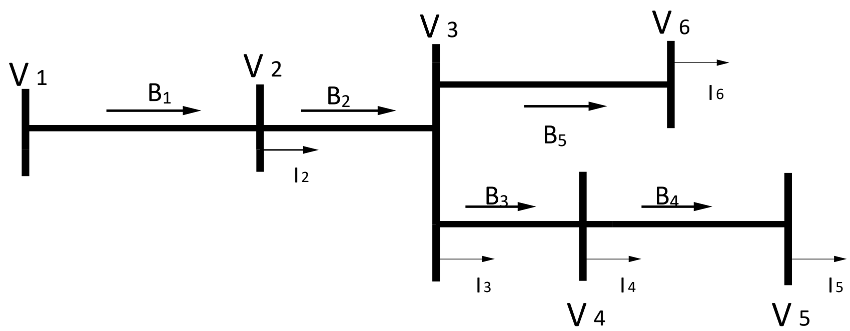

Figure 3.4: Simple 6-bus distribution network

Formation of BIBC Matrix/Backward Sweep

Using Kirchhoff's current law (KCL) [52] the branch currents are obtained as a function of injected currents at each bus to the radial distribution network as shown above in Figure 3.4. The injected currents at each bus are calculated using equation (3.25) and the branch currents B_5, B_4, B_3, B_2, and B_1, B_n can be formulated as shown below.

$$B_1 = I_2 + I_3 + I_4 + I_5 + I_6 \quad (3.26)$$

$$B_2 = I_3 + I_4 + I_5 + I_6$$

$$B_3 = I_4 + I_5$$

$$B_4 = I_5$$

$$B_5 = I_6 \quad (3.27)$$

Equations from (3.26) to (3.27) is given in matrix form as follows:

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \quad (3.28)$$

Equation (3.28) in a compact form is given as follows:

$$[B] = [BIBC]\,[I] \quad (3.29)$$

Where, [BIBC] is the relationship matrix between branch currents and bus current injections

Formation of BCBV matrix/Forward Sweep

Appling Kirchhoff's Voltage Law (KVL) [52] the branch current to bus voltage (BCBV) matrix which is the relationship of branch currents and bus voltages of the network can be obtained. Voltages of the nodes 2, 3, 4…n in Figure 3.7 are expressed as:

$$V_2=V_1-Z_{12}B_1 \quad (3.30)$$

$$V_3=V_2-Z_{23}B_2$$

$$V_4=V_3-Z_{34}B_3 \quad (3.31)$$

$$V_5=V_4-Z_{45}B_4$$

$$V_6=V_3-Z_{36}B_5 \quad (3.32)$$

Where, V_i voltage at bus i and Z_{ij} is line impedance between bus i and bus j

Equations from (3.30) to (3.32) can be written in a matrix form as follows:

$$\begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \quad (3.33)$$

The general form for the bus voltage at $(k+1)^{th}$ iteration from equation (3.33) can be expressed as:

$$[V^{k+1}] = [V_1] - [BCBV]\,[B] \quad (3.34)$$

We can write equation (3.34) as $[V_1]$ - $[V^{k+1}]$ = [BCBV] [B] and substitute [BIBC] [I] for [B], and let $\Delta V= [V^{k+1}] - [V_1]$, the relations between the node current injections and node voltages could be write as:

$$\Delta V=[V_1] - [V^{k+1}] \quad (3.35)$$

$$\Delta V = [BCBV]\,[BIBC]\,[I] \quad (3.36)$$

$$[DLF] = [BCBV]\,[BIBC] \quad (3.37)$$

where, DLF (distribution load flow matrix) is the relationship matrix between voltage drops and bus current injections.

Substituting equation (3.37) into equation (3.36), we have

$$[\Delta V] = [DLF]\,[I] \tag{3.38}$$

The iterative process stops when equation (3.41) less than or equal the given tolerance ε. This work the value of ε is 0.00001.

$$[\Delta V^{k+1}] = [DLF]\,[I^{k}] \tag{3.39}$$

$$[V^{k+1}] = [V_1] + [\Delta V^{k+1}] \tag{3.40}$$

$$|V_i^{k+1} - V_i^{k}| \le \varepsilon \tag{3.41}$$

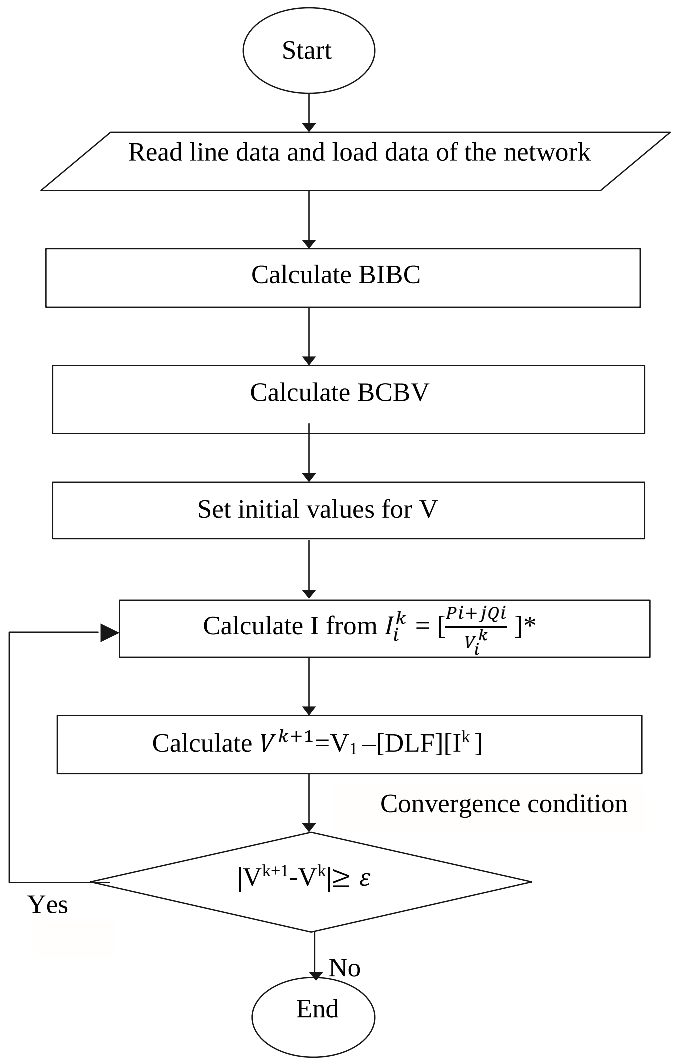

Figure 3.5: Flowchart for the proposed load flow algorithm

3.3.3 Harmonic Power Flow Analysis

The harmonic power flow algorithm (HPF) is the most commonly used method to estimate the harmonic distortion, and was introduced by Teng [53]. The flowchart of HPF analysis is shown in Figure 3.7. HPF is backward forward sweep technique at which effect of harmonics is also considered. The matrix [A] is calculated using the backward sweep in HPF algorithm, on the other hand the matrix [HA] is calculated using forward sweep in HPF algorithm. To explain, the HPF algorithm, an unbalanced six bus radial distribution system shown in Figure 3.6 is considered, assuming bus 1 as slack bus.

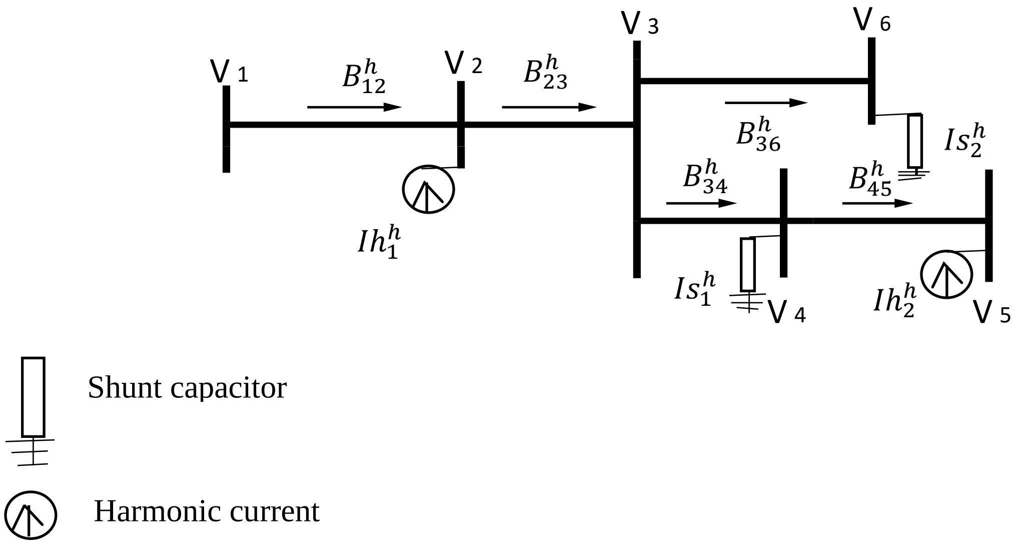

Figure 3.6: 6-bus harmonic distribution network

The h^{th} harmonic currents injected to network can be expressed as follows:

$$[Ih^h] = \begin{bmatrix} Ih_1^h \\ Ih_2^h \\ \ldots \\ Is_1^h \\ Is_2^h \end{bmatrix} \tag{3.42}$$

where, Ih^h =h-th harmonic current vector of the network.

Ih_1^h, Ih_2^h ...=h-th harmonic currents injected by nonlinear loads (such as DG units). Is_1^h, Is_2^h ...=h-th harmonic current absorbed by shunt capacitors.

KCL is applied in the backward sweep method to calculate the current flowing in branches,

$$B_{12}^h = Ih_1^h + Ih_2^h + \ldots + Is_1^h + Is_2^h \tag{3.43}$$

$$B_{23}^h = Ih_2^h + \ldots + Is_1^h + Is_2^h \tag{3.44}$$

$$B_{34}^h = Ih_2^h + \ldots + Is_1^h \tag{3.45}$$

$$B_{45}^h = Ih_2^h + \ldots \tag{3.46}$$

$$B_{36}^h = \ldots + Is_2^h \tag{3.47}$$

Equations from (3.43) to (3.47) in a matrix form are given by:

$$\begin{bmatrix} B_{12}^h \\ B_{23}^h \\ B_{34}^h \\ B_{45}^h \\ B_{36}^h \end{bmatrix} = \begin{bmatrix} 1 & 1 & \dots & 1 & 1 \\ 0 & 1 & \dots & 1 & 1 \\ 0 & 1 & \dots & 1 & 0 \\ 0 & 1 & \dots & 0 & 0 \\ 0 & 0 & \dots & 0 & 1 \end{bmatrix} \begin{bmatrix} Ih_1^h \\ Ih_2^h \\ \dots \\ Is_1^h \\ Is_2^h \end{bmatrix} \quad (3.48)$$

Equation (3.48) can also be expressed as follows:

$$[B^h] = [A]\,[Ih^h] \quad (3.49)$$

where, $[A^h]$ represent relationship between bus current injection and branch current flows at h^{th} harmonic. The h^{th} harmonic branch current of a specific branch is given by:

$$[B_{ij}^h] = [A_{ij}^h]^T [Ih^h] \quad (3.50)$$

where, $[A_{ij}^h]$ the coefficient vector of branch *(i-j)*:

$$[A_{ij}^h] = \begin{bmatrix} Ah_{12}^h \\ Ah_{23}^h \\ \dots \\ As_{12}^h \\ As_{23}^h \end{bmatrix} \quad (3.51)$$

where, $[Ah_{ij}^h]$ =the coefficient vector of branch (*i-j)* due to the harmonic current flows of the loads through branch (*i-j)*, $[As_{ij}^h]$ =the coefficient vector of branch (*i-j)* due to the harmonic currents absorbed by the shunt capacitors.

The harmonic voltage drop between buses 1 and 2:

$$\Delta V_{12}^h = Z_{12}^h\, B_{12}^h \quad (3.52)$$

KVL is applied in the forward sweep method to calculate harmonic bus voltages.

$$V_2^h = V_1^h - Z_{12}^h\, B_{12}^h \quad (3.53)$$

$$V_3^h = V_1^h - Z_{12}^h\, B_{12}^h - Z_{23}^h\, B_{23}^h$$

$$V_4^h = V_1^h - Z_{12}^h\, B_{12}^h - Z_{23}^h\, B_{23}^h - Z_{34}^h\, B_{34}^h \quad (3.54)$$

$$V_5^h = V_1^h - Z_{12}^h\, B_{12}^h - Z_{23}^h\, B_{23}^h - Z_{34}^h\, B_{34}^h - Z_{45}^h\, B_{45}^h$$

$$V_6^h = V_1^h - Z_{12}^h\, B_{12}^h - Z_{23}^h\, B_{23}^h - Z_{36}^h\, B_{36}^h \quad (3.55)$$

where, V_1^h the slack bus voltage at h^{th} harmonic order

slack bus voltage is zero, hence by substituting equation (3.50) into equations from (3.53) through (3.55) we get,

$$V^h = [HA^h]\,[Ih^h] \tag{3.56}$$

where, V^h =h-th harmonic bus voltages vector,

$[HA^h]$ =the relationship matrix between the harmonic bus voltages and currents

The harmonic bus voltage of the shunt capacitor is determined by:

$$V_s^h = [HA_s^h]\,[Ih^h] \tag{3.57}$$

where, $[HA_s^h]$ = the row vectors of the matrix $[HA^h]$ associated with the bus at which shunt capacitor is placed.

The harmonic voltage of shunt capacitor placed at bus *i* in terms of its harmonic impedance is given as follows:

$$V_{si}^h = -I_{si}^h Z_{si}^h \tag{3.58}$$

where, I_{si}^h =the harmonic current of shunt capacitor placed at bus *i*

Z_{si}^h =the harmonic impedance of filter placed at bus i

Substituting Equation (3.58) into Equation (3.57), we get:

$$-I_{si}^h Z_{si}^h = [HA_s^h]\begin{bmatrix} Ih_1^h \\ Ih_2^h \\ \dots \\ Is_1^h \\ Is_2^h \end{bmatrix} \tag{3.59}$$

In matrix $[HA_s^h]$ the elements of the first columns are related to the harmonic currents of loads and the last element is related to the harmonic current of the shunt capacitor placed at bus *i*. So it can be written as:

$$[HA_s^h] = [HA_{sh}^h \,\vdots\, HA_{ss}^h] \tag{3.60}$$

Solving equation (3.59) to get I_{si}^h,

$$I_{si}^h = [HLF^h]^{-1}[HA_{sh}^h]\,[Ih^h] \tag{3.61}$$

where, $[HLF^{h}]$=($[HA_{ss}^{h}]$+ Z_{si}^{h}) , HLF=harmonic load flow

The harmonic bus voltages are calculated iteratively until a predefined tolerance ε is reached.

$$|V_i^{h,k+1} - V_i^{h,k}| \leq \varepsilon \tag{3.62}$$

where, $V_i^{h,k+1}$ = h-th harmonic voltage of bus i for iteration k +1

$V_i^{h,k}$ = h-th harmonic voltage of bus i for iteration k

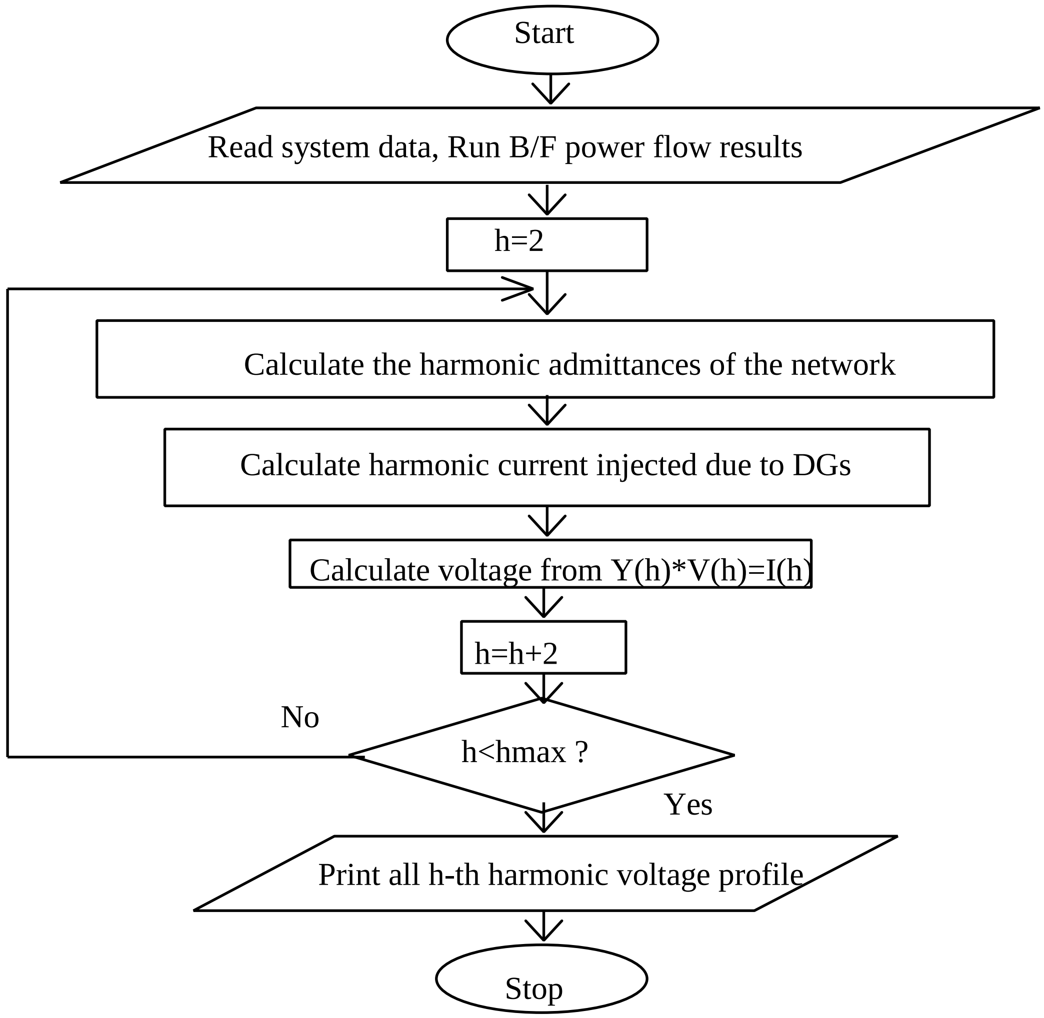

Figure 3.7: Flowchart of HPF analysis

Finally, the total harmonic distortion at bus i can be calculated from the following equation:

$$\mathrm{THDvi} = \sqrt{\frac{\sum_{h=5}^{hmax} |V_i^h|^2}{|V_i^1|^2}} \tag{3.63}$$

where, h=5, 7, 11…..hmax (hmax=17), $|V_i^h|$=h-th harmonic bus voltage at bus i, $|V_i^1|$=fundamental bus voltage at bus i.

The result of the normal backward forward sweep used to calculate the harmonic admittance. Harmonic voltage is obtained from the nodal equations, and then the harmonic distortion can be calculated from corresponding results.

3.4 Particle Swarm Optimization (PSO)

Population size, number of iterations, velocity components, and acceleration coefficients are the basic PSO parameters [40].

- ✓ Population size is the number of particles in the swarm. A big swarm size increase the computational complexity per iteration, and more time consuming while the result is good.
- ✓ The number of iterations helps for a good result of the problem.
- ✓ Velocity components are used for updating particle's position.
- ✓ Acceleration coefficients c_1 and c_2, together with the random values r_1 and r_2, maintain the stochastic influence of the cognitive and social components of the particle's velocity respectively. From the different empirical researches [40], it has been proposed that the two acceleration constants should be $c_1 = c_2 = 2$.

In PSO, each particle of the swarm modifies its position by the following information: The particle current positions (X_i), the particle current velocity (V_i), the distance between the current position and Pbest, and the distance between the current position and Gbest. In accordance with the equation (3.67) and equation (3.68) every particle updates its velocity and position to give the most optimal solution [11]. In this thesis work the parameters that are considered are c_1=c_2=2, population size=250, maximum iteration=60.

$$V_i^{k+1} = \omega * V_i^k + c_1 * r_1 * \left(Pbest_i - X_i^k\right) + c_2 * r_2 * (Gbest - X_i^k) \tag{3.67}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{3.68}$$

Where V_i^k is the current velocity the i^th particle at iteration k, r_1 , r_2 are random number between 0 and 1, X_i^k is the current position of the i-th particle at k-th iteration, c_1, c_2 are the acceleration coefficients, $Pbest_i$ is the personal best position of the i-th particle, $Gbest$ is the global best position of the group, ω is the inertia weight.

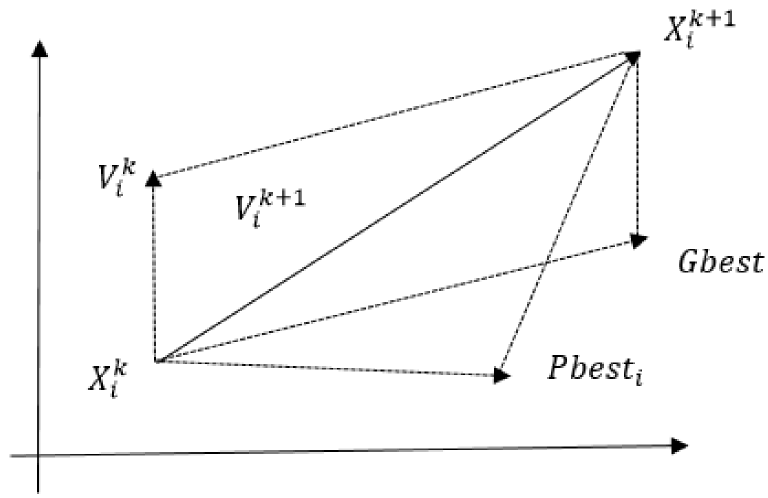

Figure 3.8**:** PSO searching concept [35]

PSO algorithm for finding the optimal place and size of DG units are given in a flow chart in Figure 3.9 and also the steps are listed as follows.

Step 1. Give input bus and line data of test system.

Step 2. Randomly initialize particle position and particle velocity.

Step 3. Run B/F sweep power flow for fundamental frequency case.

Step 4. Calculate harmonic admittance matrix for each harmonic order h.

Step 5. Run harmonic power flow algorithm for estimating the harmonic voltage components.

Step 6. Evaluate objective function of each individual particle with the penalty function, if there is any constraint violation and then, *Pbest* and *Gbest* vectors are found.

Step 7. Print the results if termination criterion is satisfied otherwise, go to step 8.

Step 8. Update velocity and particle position and then the process is again go to step 2.

Step 9. Optimal location and capacity of DG units are taken as output.

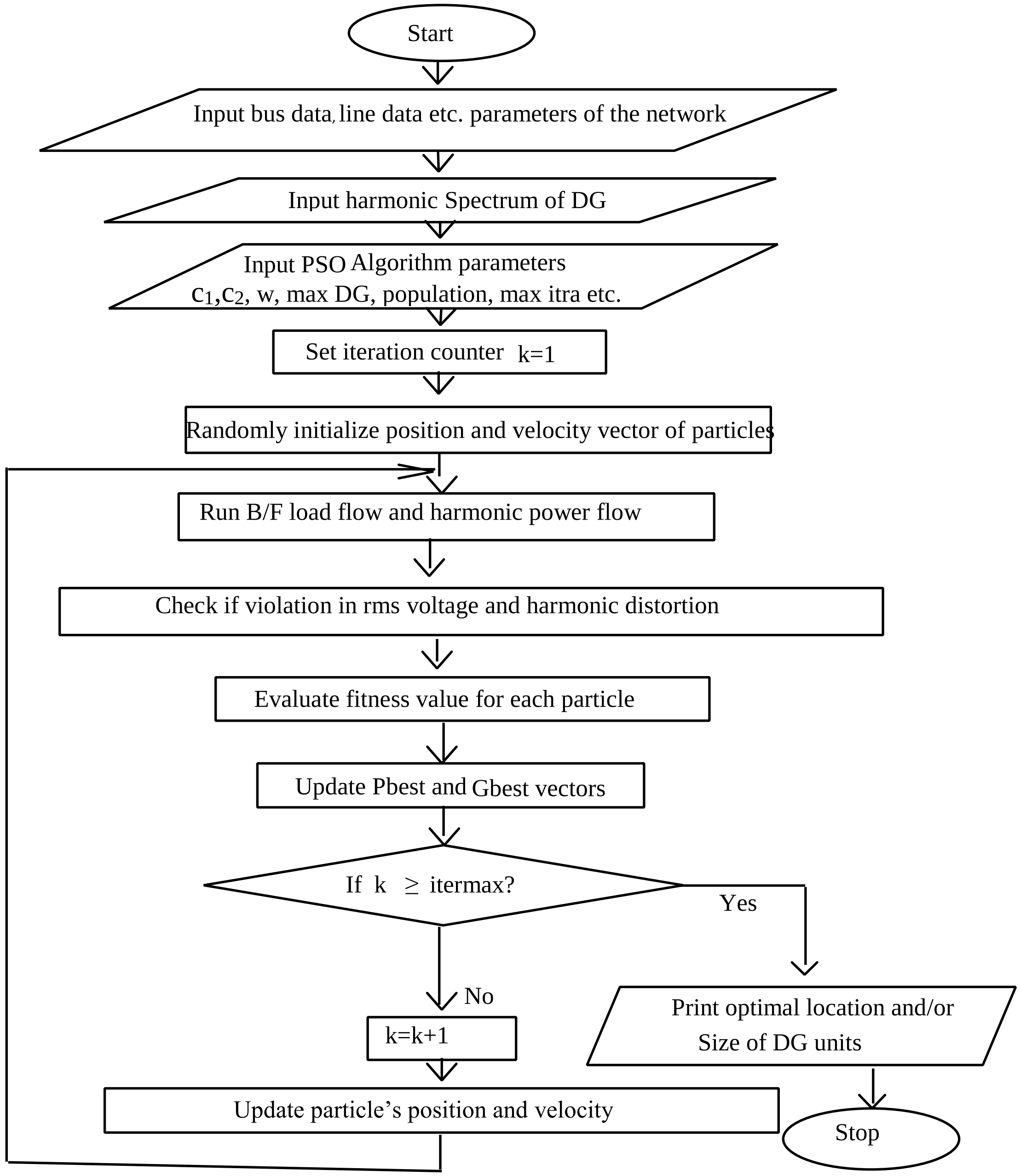

Figure 3.9: Flowchart of PSO based optimal DG location and/or sizing

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Results and Discussion for Case Study 78-Bus Radial Distribution System

4.1.1 Integration of Type 1 DGs

The PSO algorithm was applied to get the optimal DG units places and sizes for 78-bus radial distribution system. Those buses with highest positive value of loss sensitivity index are considered as candidate bus for DG unit installation, in order to increase the probability of the optimal DGs placement. Three critical buses with highest positive values of LSI were 67, 36 and 30. Having been running the proposed algorithm, the optimal locations are obtained at buses 30, 36 and 67 with optimal sizes of 1911.8 kW, 2029.5 kW and 2393.2 kW respectively, and it is given Table 4.2.

Table 4.2: Optimal location and size of type 1 DG units for 78-bus network.

Bus number	Size of DG (kW)
30	1911.8
36	2029.5
67	2393.2

It is obtained each DGs capacity is below 90% of the total load as expected. The bus voltage profile (V) and voltage stability index (VSI) obtained from the load flow before placement (base case) and after placement of DG unit in the 78-bus radial distribution network are shown below in Figure 4.10. And from both figures which are represented by the red colors it can be seen that both the voltage profile and VSI are substantially improved.

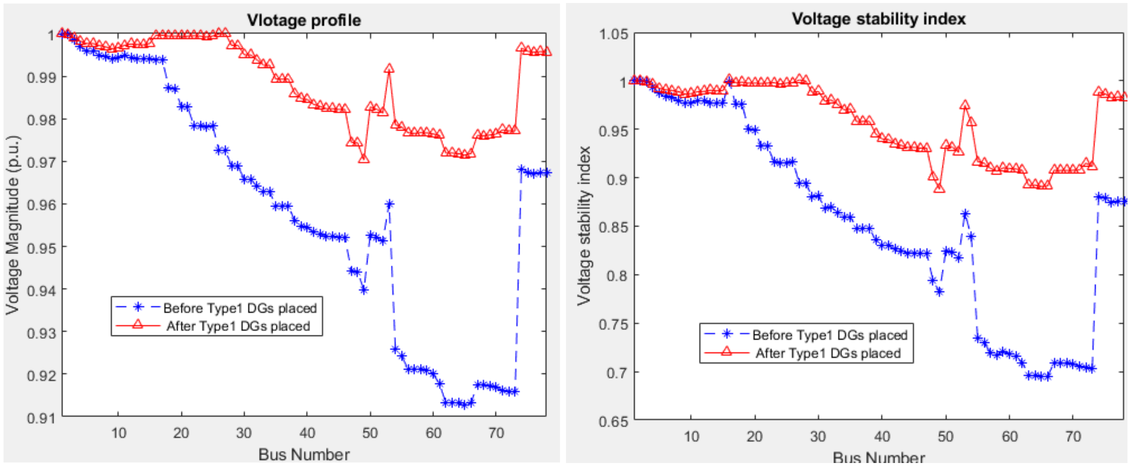

Figure 4.10: Voltage profile and VSI for 78-bus network with and without type 1 DGs.

Running the B/F sweep and HPF the base case results, for 78-bus system the minimum voltage was 0.91283, at bus 65, while the minimum VSI was 0.69473 at bus 65, as well as the average voltage total harmonic distortion (THDv) was 0.0377 and the total active and reactive loss was 389.3678 kW and 256.1723 kVar respectively. After placing the DG units using PSO, the minimum voltage is 0.96941, at bus 49 while the minimum VSI is 0.88505 at bus 49, the average THDv is 0.0338 and the total active and reactive loss is 123.1364 kW and 83.485 kVar respectively. This brings a 6.19% improvement on the minimum voltage, 27.39% improvement on the minimum VSI, the average voltage total harmonic distortion is reduced from 3.77% to 3.38% and it is below 5% the maximum standard limit of IEEE-519 and the total active power loss and the total reactive power loss are reduced significantly from 389.3678kw to 123.1364kw and from 256.1723kVar to 83.485kVar respectively.

Table 4.3: Improvement in voltage and VSI for 78-bus with type 1 DGs.

Bus number		30	36	67
Vbus in pu	Before DG	0.96578	0.95946	0.91754
	After DG	0.99086	0.98887	0.97752
	% improvement	2.59	3.06	6.53
VSI	Before DG	0.88011	0.84741	0.70936
	After DG	0.96695	0.95891	0.91287
	% improvement	9.86	13.15	28.68

Voltage profile and VSI improvement is occurred at all buses of the proposed network, however, the most significant improvement have been occurred at those close or at which the DGs were integrated as shown in Table 4.3. The weakest buses no longer the weakest after the installation of the DGs.

4.1.2 Integration of Type 2 DGs

The critical buses that has the highest positive values of LSI were 75, 59 and 56. Having running the proposed algorithm, the optimal locations obtained are at buses 59, 75 and 56, and their optimal sizes are 1419.2 kVar, 4517.3 kVar and 1042.2 kVar respectively.

Table 4.4: Optimal sizes and location of type 2 DG units for 78-bus.

Bus number	Size of DG (kVar)
59	1419.2
75	4517.3
56	1042.2

From the base case, the minimum voltage for the 78-bus network was 0.91283, at bus 65, while the minimum VSI was 0.69473 at bus 65, as well as the average voltage total harmonic distortion (THDv) was 0.0377 and the total active and reactive loss was: 389.3678 kW and 256.1723 kVar respectively. After placing the type 2 DG units using PSO, the network's minimum voltage is: 0.9500, at bus 65 while the minimum VSI is 0.81495 at bus 65, the average THDv is 0.0352 and the total active and reactive power loss is: 352.7461 kW and 229.4969 kVar respectively. This represents a 4.07% improvement on the minimum voltage, 17.3% improvement on the minimum VSI, the average voltage total harmonic distortion is reduced from 3.77% to 3.52% and it is below 5% the maximum standard limit of IEEE-519 and the total P and Q loss are little reduced from 389.3678kw to 352.7461kw and from 256.1723kVar to 229.4969kVar respectively.

The bus voltage profile (V) and voltage stability index (VSI) obtained from the load flow before placement (base case) and after placement of DG unit in the 78-bus radial network are shown below in Figure 4.11. It can be observed that both the voltage profile and VSI are considerably improved which are represented by the red color in both figures.

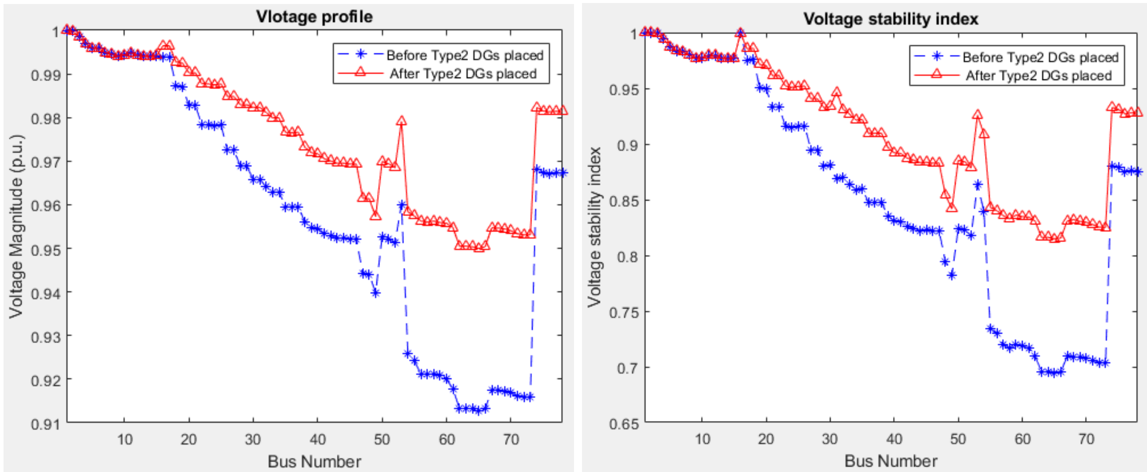

Figure 4.11: Voltage and VSI for 78-bus network with and without type 2 DGs.

Table 4.5: Improvement in voltage profile and VSI for 78-bus with type 2 DGs.

Bus number		59	75	56
Vbus in pu	Before DG	0.92078	0.96735	0.92124
	After DG	0.95764	0.98758	0.9580
	% improvement	4.00	2.09	3.99
VSI	Before DG	0.72026	0.87863	0.72965
	After DG	0.84229	0.94219	0.84542
	% improvement	16.94	7.23	15.86

Most significant percentage improvement in voltage profile and VSI is given in Table 4.5 in which optimally the type 2 DG units were placed in the 78-bus network.

4.1.3 Integration of Type 3 DG Units those Injecting Both Powers

The critical buses were 17, 21 and 25. The optimal locations are obtained at buses 54, 71 and 30, and their optimal sizes are 614.23 -j400.09kVA, 1090.1 - j710.05kVA and 2860.8 - j1863.5 kVA respectively. It can be also observed from Figure 4.12 that after optimally placed Type 3 DGs on the 78-bus network both voltage profile and VSI are substantially improved.

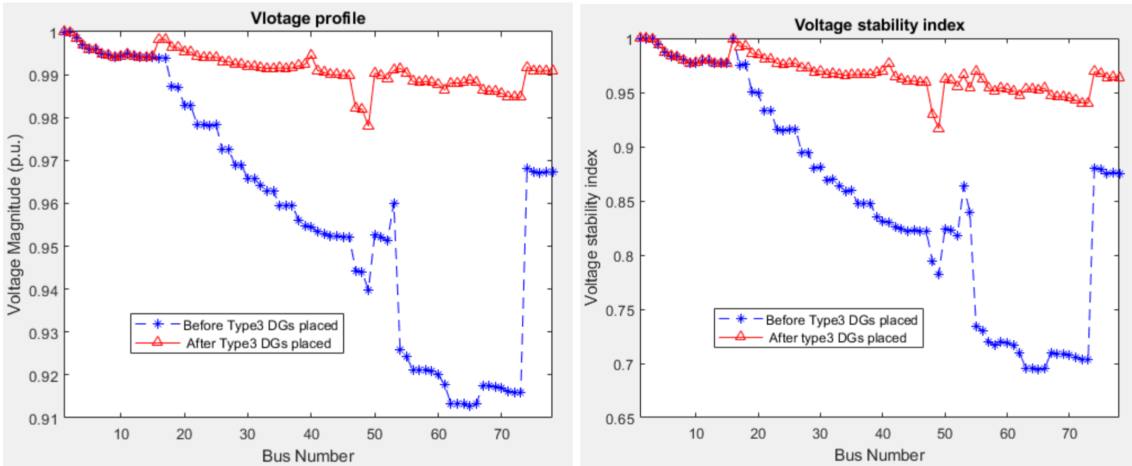

Figure 4.12: Voltage and VSI for 78-bus network with and without type 3 DGs.

For the 78-bus network the minimum voltage was 0.91283, at bus 65, while the minimum VSI was 0.69473 at us 65, as well as the average voltage total harmonic distortion (THDv) was 0.0377 and the total active and reactive loss was: 389.3678 kW and 256.1723 kVar respectively. Having placed the type 3 DG units using PSO, the network's minimum voltage is: 0.97496, at bus 49 while the minimum VSI is 0.90546, at bus 49, the average THDv is 0.0329 and the total P and Q loss is: 79.9017 kW and 56.3666 kVar respectively. This brought about 6.8% improvement on the minimum voltage, 30.3% improvement on the minimum VSI, the average voltage total harmonic distortion is reduced from 3.77% to 3.29% and it is below 5% the maximum standard limit of IEEE-519 and the total active power and reactive power loss are substantially reduced from 389.3678kw to 79.9017 kW and from 256.1723kVar to 56.3666 kVar respectively.

4.1.4 Comparisons between the Integration of Type 1, 2 and Type 3 DG Units

The minimum voltage profile is improved 6.19% in case of type 1 DG units, whereas the improvement in case of type 2 DG unit is 4.07% while it is 6.8% in case of type 3 DGs, and the minimum voltage stability index is also improved 27.39% in case of type 1 DG unit integration, whereas in case of type 2 DG units shows 17.3% improvement while it is 30.3% in case of type 3 DGs. The average voltage total harmonic distortion is reduced from 3.77% to 3.38%, from 3.77% to 3.52% and from 3.77% to 3.29% in case of type 1, type 2 and type 3 DGs respectively, in all cases it is below 5% which is the maximum IEEE-519 standard limit. The total active and reactive power loss are reduced significantly from 389.3678kw to 123.1364kw and from 256.1723kVar to 83.485kVar respectively in case of integration of type 1 DGs, while in case type 2 DGs the total active and reactive power loss are little reduced from 389.3678kw to 352.7461kw and from 256.1723 kVar to 229.4969 kVar respectively. Whereas, in case of type 3 DGs the total active power loss and total reactive power loss are substantially reduced from 389.3678kw to 79.9017 kW and from 256.1723kVar to 56.3666 kVar respectively. From the results it can be observed that the integration of type 1 and type 3 DG units in distribution network are better for the improvement of voltage and voltage stability while keeping reduced the power loss and total harmonic distortion this is due to the active power demand of the network is relatively high, and both Type of DGs inject active power and significantly reduce the voltage drop.

4.2 Results and Discussion for IEEE-69 Bus Radial Distribution Network

4.2.1 Integration of Type 1 DGs

The applicability of the proposed method is also tested on standard IEEE-69 bus radial distribution network. Candidate buses for DG unit installation are selected using highest positive value of loss sensitivity index, in order to increase the probability of the optimal DGs placement. Three critical candidate locations has been proposed in buses 59, 61, and 11 these buses which have the highest positive loss sensitivity index. The optimal sizes and location of DG units obtained using PSO are given in Table 4.6.

Table 4.6: Optimal type 1 DGs location and size for IEEE-69 bus.

Bus number	Size of DG unit (kW)
50	717.31
11	913.17
59	1818.8

The optimal type 1 DG locations are at bus 50, 11 and 59, and the optimal DGs size are 717.31 kW, 913.17 kW and 1818.8 kW respectively. Each size of the placed DG units are below 90% of the total load. By running the proposed load flow Figure 4.13 shows voltage profile and VSI obtained before and after integration of the DG units in the standard 69-bus network.

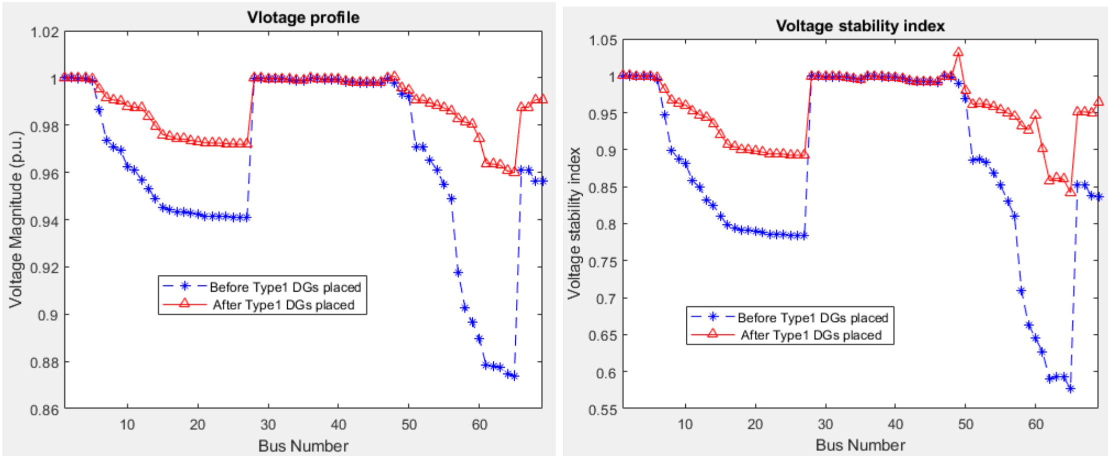

Figure 4.13: Voltage profile and VSI before and after place of type 1 DGs in the 69-bus.

From the base case running the B/F sweep and HPF results, for the standard 69-bus network the minimum voltage was 0.87387, at bus 65 while the minimum VSI was 0.57713 at bus 65. The total active and reactive power loss was 322.2154 kW and 144.0729 kVar respectively. And the average voltage total harmonic distortion (THDv) was 0.0151. After placing the type 1 DGs using PSO, the network's minimum voltage obtained is 0.95997, at bus 65 while the minimum VSI is 0.84196 at bus 65. The total P and Q loss is 96.2654 kW and 52.3157 kVar respectively, and the THDv is 0.0136. The minimum voltage has improved 9.85%, and 45.88% improvement have been obtained on the minimum VSI. The total active power and reactive power loss are significantly reduced from 322.2154 kW to 96.2654 kW and from 144.0729 kVar to 52.3157 kVar respectively. The average THDv is also reduced from 1.51% to 1.36% and it is with in the IEEE-519 standard limit.

It can be observed from Figure 4.13 that great change of voltage profile and VSI have occurred at weak buses after the integration of type 1 DG units in the standard 69-bus network. From the Table 4.7 it is clear that the insertion of DGs considerably improved voltage profile and voltage stability at buses with DGs integrated.

Table 4.7: Voltage and VSI improvement with type 1 DGs in IEEE-69 bus network.

Bus number		50	11	59
Vbus in pu	Before DG	0.99224	0.96105	0.89663
	After DG	0.99509	0.99162	0.9807
	% improvement	0.28	3.18	9.37
VSI	Before DG	0.96932	0.85812	0.66348
	After DG	0.97857	0.9667	0.92769
	% improvement	0.95	12.65	39.82

4.2.2 Integration of Type 2 DGs

The three most critical candidate locations has been proposed in buses 61, 49, and 50 these buses has the highest positive loss sensitivity index. The optimal sizes and site of DG units obtained using PSO are given in Table 4.8.

Table 4.8: Optimal type 2 DGs location and size for IEEE-69 bus network.

Bus number	Size of DG unit (kVar)
61	1285.9
50	520.76
16	376.4

The optimal locations of type 2 DG units obtained in the standard 69 bus network using PSO are at bus 61, 50 and 16, and their optimal sizes are 1285.9 kVar, 520.76 kVar and 376.4 kVar respectively. From Figure 4.14 it can be also observed that after type 2 DG unit optimal placement in the standard 69-bus system, the voltage profile and voltage stability of the network are considerably enhanced.

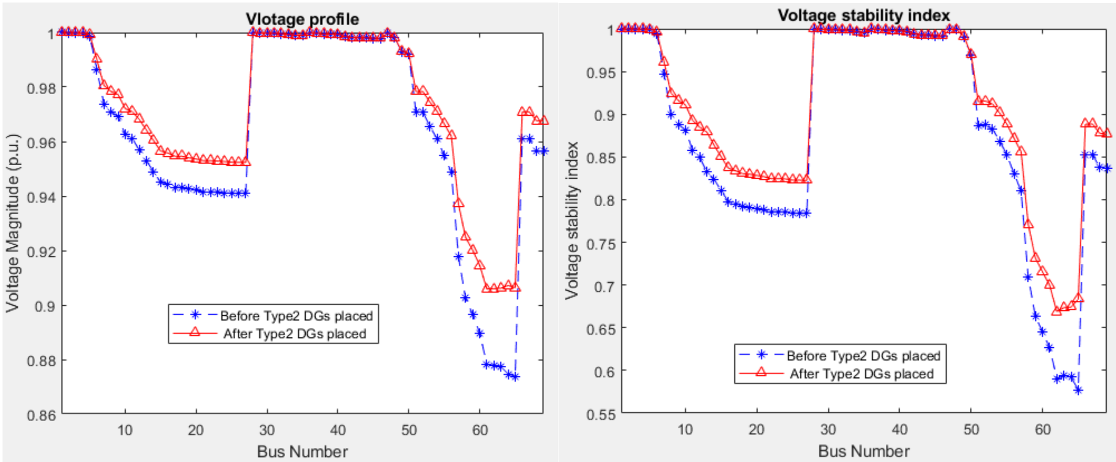

Figure 4.14: Voltage and VSI for 69-bus network with and without type 2 DGs.

In case of integration of type 2 DG units in the standard 69-bus network using PSO, the minimum voltage profile is at bus 61 and is improved from 0.87387 to 0.90523 with percentage of 3.58%, while the minimum VSI is at bus 62 and is improved from 0.57713 to 0.66499, it reveals 15.22% improvement. The total active and reactive power loss are considerable reduced from 322.2154 kW to 204.7135 kW and from 144.0729 kVar to 91.8765 kVar respectively. And the average voltage total harmonic distortion is little reduced from 0.0151 to 0.0145 while it is with in the standard harmonic limits.

Similarly Table 4.9 shows that high percentage of voltage profile and VSI improvement on the optimal DGs locations in the standard 69-bus network.

Table 4.9: Voltage and VSI improvement with type 2 DGs in 69-bus network.

Bus number		61	50	16
Vbus in pu	Before DG	0.87821	0.99224	0.94439
	After DG	0.90941	0.99724	0.95794
	% improvement	3.55	00.5	1.43
VSI	Before DG	0.62661	0.96932	0.79786
	After DG	0.70867	0.98557	0.84381
	% improvement	13.09	1.67	5.75

4.2.3 Integration of Type 3 DG Units these Injecting Both Powers

The optimal locations of type 3 DG units obtained in the standard 69 bus network using PSO are at bus 61, 49 and 12, and their optimal sizes are 1101.7 - j783.02 kVA, 851.36 - j605.11 kVA and 559.41 - j397.61 kVA respectively. It can be also observed from Figure 4.15 that after optimal placement of Type 3 DGs on standard 69-bus network both voltage profile and voltage stability index are significantly improved.

The minimum voltage profile was 0.87387 at bus 65 before Type 3 DGs placement, after placement of type 3 DGs on the standard 69-bus network, it is improved to 0.9824, at bus 27 with percentage of 12.41%, while the minimum VSI is enhanced from 0.57713 to 0.93145, at bus 27, it reveals 61.39% improvement. The total active and reactive power loss are substantially reduced from 322.2154 kW to 58.0036 kW and from 144.0729 kVar to 28.2914 kVar respectively. And the average voltage total harmonic distortion is reduced from 0.0151 to 0.0130 while it is with in the standard harmonic limits.

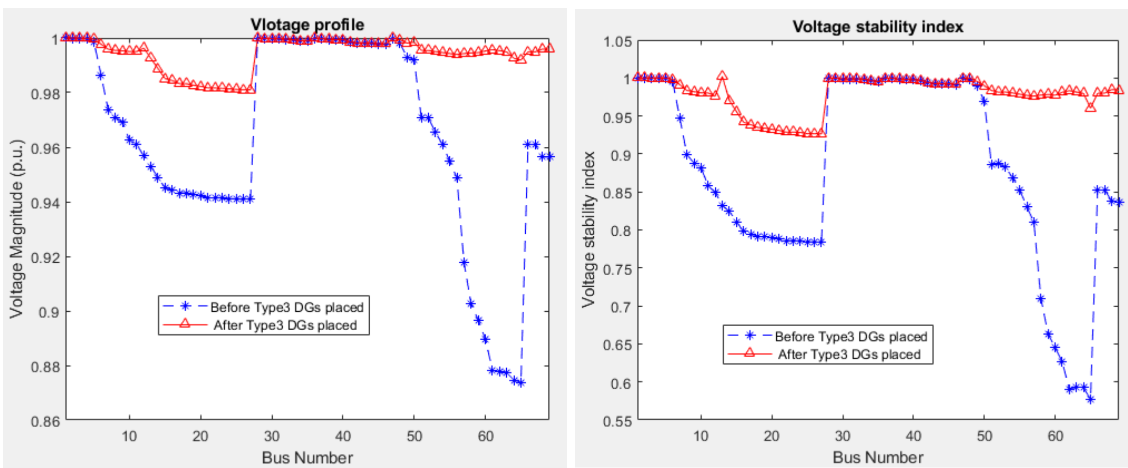

Figure 4.15: Voltage and VSI for 69-bus network with and without type 3 DGs.

4.2.4 Comparisons between the Integration of Type 1, 2 and Type 3 DG Units

The minimum voltage profile is improved 9.85% in case of type 1 DG units, whereas the improvement in case of type 2 DG unit is 3.58% while it is 12.41% in case of type 3 DGs, and the minimum VSI is also improved 45.88% in case of type 1 DG unit integration, whereas in case of type 2 DG units shows 15.22% improvement while it is 61.39% in case of type 3 DGs. The total active power loss and total reactive power loss are significantly reduced from 322.2154 kW to 96.2654 kW and from 144.0729 kVar to 52.3157 kVar respectively in case of type 1 DGs, whereas, in case of type 2 DGs the total active and reactive power loss are considerably reduced from 322.2154 kW to 204.7135 kW and from 144.0729 kVar to 91.8765 kVar respectively , while in case of type 3 DGs the total active and reactive power loss are substantially reduced from 322.2154 kW to 58.0036 kW and from 144.0729 kVar to 28.2914 kVar respectively. The average voltage total harmonic distortion is reduced from 1.51% to 1.36%, from 1.51% to 1.45% and from 1.51% to 1.30% in case of type 1, type 2 and type 3 DGs respectively, in all cases it is below the maximum standard harmonic limit. From these results it can be observed that the integration of type 1and type 3 DG units are better for the improvement of voltage profile and voltage stability in distribution network while keeping reduced the power loss and total harmonic distortion.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

PSO based algorithm was developed for placing of DG units in distribution networks. The backward/forward sweep technique and harmonic load flow method was used to calculate network parameters. Active power loss and voltage stability index based objective function was successfully formulated. Voltage profile, VSI, power loss and THDv were calculated for both 78-bus and standard 69-bus radial distribution networks. Comparison between the integration of type 1, 2 and type 3 DG units interims of voltage profile, VSI, THDv and power loss were conducted. In the 78-bus network when the DG unit placement was done using the PSO method, both voltage profile and VSI were improved in case of type 1, 2 and type 3 DG units, in all cases the THDv was below 5% which is the maximum IEEE-519 standard harmonic limits. The total active and reactive power loss were significantly reduced in case of integration of type 1 and type 3 DGs, while in case type 2 DGs the total active power loss and total reactive power loss were little reduced. Similarly, the PSO method was also used to place and size DG units in the standard 69 bus network, and improved the system voltage profile, voltage stability, and reduced the power loss while keeping the total harmonic distortion of the system within the standard harmonic limits.

Even though, integration of type 2 DG units can influence the voltage stability directly by injecting reactive power to the system, integrating of type 1 DG units such as PV Solar and Wind have significant effect not only to the voltage stability but also to the voltage profile and power loss of the system. Therefore, from the obtained results it can be concluded that the integration of type 1 and type 3 DG units are better for the improvement of voltage profile and voltage stability in distribution network while keeping reduced the power loss and total harmonic distortion. It can be also concluded that optimal placement of DG units can enhance voltage profile and voltage stability as the same time it can minimize power loss of a network, while controlling the harmonic impact caused by the DG units within the permissible standard harmonic limits.

5.2 Recommendations for Future Work

This paper developed PSO method for the optimal placement of DG units in radial distribution networks, future research work can determine another optimization method such as GA, DE, SA or hybrid of more than two optimization techniques. Only type 1, 2 and type 3 DG units were considered in this work, evaluating this work for the applicability to the placement of type 4 DGs in distribution network can be done in future. Another a multi-objective function that consider the cost of DG placement together with voltage stability and power loss can be developed. This work also discussed the optimal placement of DG unit at the same time controlling the harmonic effect of the placement. Future work can be conducted placement of DG units with detail harmonic impact analysis and mitigations.

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APPENDEXES

Appendix I: Case Study 78-Bus Radial Distribution Network

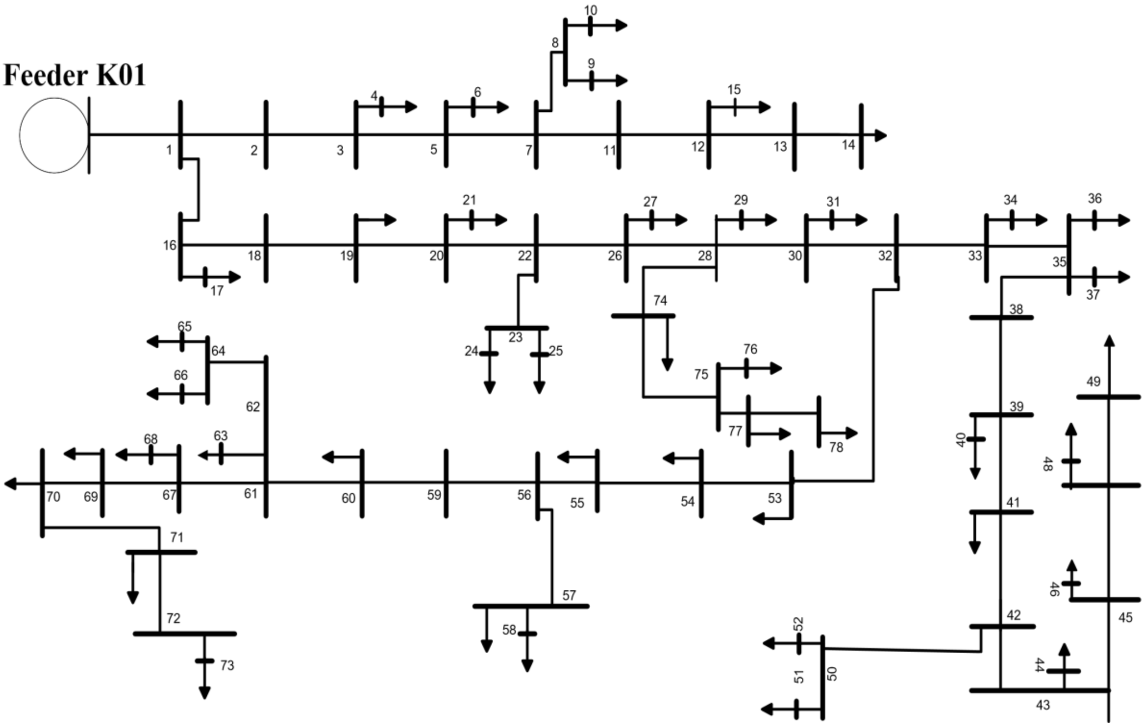

Figure A.16: Case study 78-bus radial distribution network.

Appendix II: Bus and Line Data for 78-Bus Radial Distribution Network

Table A.10: Line and bus data for local 78-bus network.

Line data					Bus data		
From	To	R(Ω)	X(Ω)	bus no.	Bus no.	P(KW)	Q(kVar)
1	2	0.029433	0.030932	1	1	0	0
2	3	0.165418	0.173847	2	2	0	0
3	4	0.193244	0.203091	3	3	0	0
4	5	0.193244	0.1245	4	4	108.4	93.8
5	6	0.009448	0.00299	5	5	0	0
6	7	0.164122	0.172485	6	6	123.2	92.4
7	8	0.126518	0.075873	7	7	0	0
8	9	0.294216	0.309208	8	8	116.8	87.6
8	10	0.171236	0.10269	9	9	176	132
7	11	0.036793	0.022065	10	10	134	98.6
11	12	0.279011	0.167323	11	11	0	0
12	13	0.102568	0.06151	12	12	0	0
13	14	0.090825	0.054467	13	13	0	0
12	15	0.061437	0.036844	14	14	180	123
1	16	0.139361	0.083575	15	15	135.2	101.4
16	17	0.087527	0.05249	16	16	176	124
16	18	0.152898	0.091693	17	17	0	0
18	19	0.009025	0.005412	18	18	202.4	111.8
19	20	0.099271	0.059533	19	19	0	0
20	21	0.128965	0.040807	20	20	132	99
20	22	0.112345	0.067373	21	21	0	0
22	23	0.040264	0.024146	22	22	0	0
23	24	0.199438	0.119603	23	23	210	100
23	25	0.011223	0.00673	24	24	144.8	108.6
22	26	0.150063	0.089993	25	25	0	0
26	27	0.008793	0.005273	26	26	120	70
26	28	0.101006	0.060573	27	27	0	0
28	29	0.259747	0.15577	28	28	150	70
28	30	0.074349	0.078137	29	29	0	0
30	31	0.203857	0.214244	30	30	192.8	144.6
30	32	0.041031	0.043121	31	31	0	0
32	33	0.071942	0.075608	32	32	0	0
33	34	0.198426	0.118996	33	33	123.2	92.4
33	35	0.242623	0.145501	34	34	0	0
35	36	0.048033	0.050481	35	35	199.2	149
35	37	0.003394	0.003566	36	36	192.8	120.6
35	38	0.255747	0.268778	37	37	0	0
38	39	0.109741	0.065812	38	38	0	0
39	40	0.170658	0.102343	39	39	116.8	87.6
39	41	0.161402	0.096793	40	40	248.8	152.6
41	42	0.053974	0.032368	41	41	0	0
42	43	0.095221	0.057104	42	42	0	0
43	44	0.038563	0.040527	43	43	135.2	101.4
43	45	0.037255	0.022342	44	44	0	0
45	46	0.01938	0.011622	45	45	200	100
45	47	2.1036	1.261529	46	46	0	0
47	48	0.112634	0.067547	47	47	161.6	116.2
47	49	2.984366	1.789725	48	48	199.2	113
42	50	0.051949	0.031154	49	49	223.2	137.4
50	51	0.404487	0.242571	50	50	100.8	75.6

Line data

From	To	R(Ω)	X(Ω)	bus no
50	52	1.402284	0.84095	51
32	53	0.193244	0.203091	52
53	54	2.1036	1.261529	53
54	55	0.112634	0.067547	54
55	56	0.165418	0.173847	55
56	57	0.166875	0.052802	56
56	58	0.637361	0.669838	57
56	59	0.041099	0.013004	58
59	60	0.056394	0.059267	59
60	61	0.192756	0.115596	60
61	62	1.24789	0.89897	61
62	63	0.03693	0.02632	62
62	64	0.04790	0.028726	63
64	65	0.23321	0.16965	64
64	66	0.06789	0.04659	65
61	67	0.02123	0.016987	66
67	68	0.041031	0.043121	67
67	69	0.03348	0.02965	68
69	70	0.071942	0.075608	69
70	71	0.184542	0.11067	70
71	72	0.091779	0.096455	71
72	73	0.017529	0.010512	72
28	74	0.199438	0.119603	73
74	75	0.259747	0.15577	74
75	76	0.203857	0.214244	75
75	77	0.04930	0.03095	76
77	78	0.07961	0.05781	77

System voltage is 15 kV

Bus data

Bus no.	P(KW)	Q(kVar)
51	198.4	129
52	189.6	67.2
53	215.2	121.4
54	181.6	136.2
55	0	0
56	120	60
57	183.2	137.4
58	0	0
59	178.4	133.8
60	0	0
61	0	0
62	104.8	78.6
63	0	0
64	143.2	107.4
65	250	128
66	0	0
67	150	70
68	210	100
69	120	80
70	192.8	144
71	248.8	167.6
72	209.2	100
73	135.2	101.4
74	0	0
75	144.8	108.6
76	105.6	79.2
77	116.8	87.6
78	105.6	79.2

Table A.11: AAC conductor GMR Factor for different number of strands.

Conductor number of strands	GMR factor, k
1	0.7788
3	0.6778
7	0.7256

Table A.12: Parameters of the feeder line conductor of the network.

Type of line conductor	AAC	AAC	AAC	AAC
Nominal area in mm^2	120	95	50	25
Actual area in mm^2	117	93.5	49.5	24.2
Diameter of stranding and wire in mm	19/2.8	19/2.5	7/3.0	7/2.1
Resistance in Ω /km	0.2853	0.3085	0.5785	1.181
Overall diameter in mm	14	12.5	9	6.3
Actual diameter in mm	12.2	10.8975	7.9377	5.56
GMR in mm	9.24	4.129	2.88	1.88

Appendix III: IEEE Standard 69 Bus Radial Distribution Network

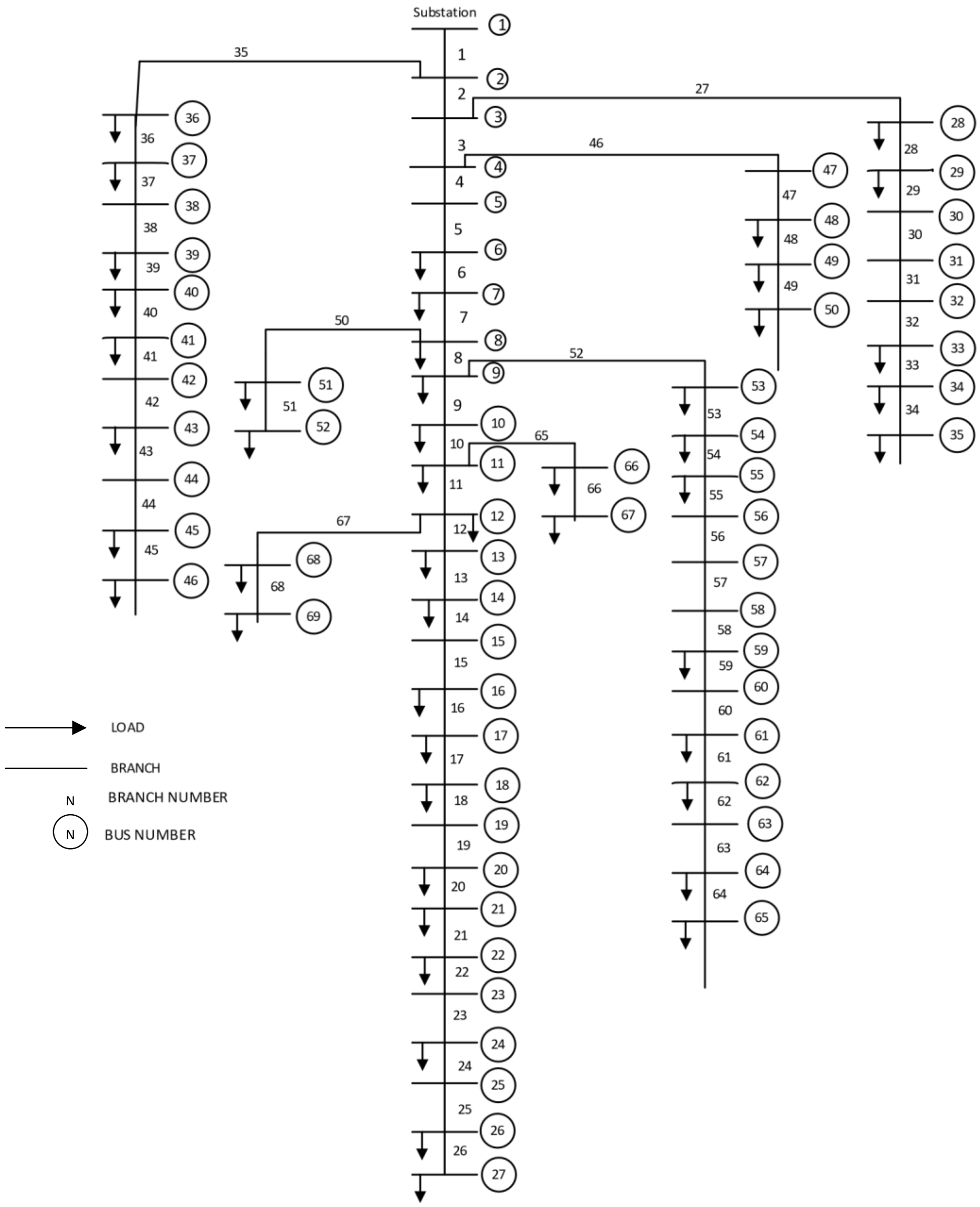

Figure A.17: IEEE standard 69-bus network line diagram

Appendix IV: Bus and Line Data for IEEE-69 Bus Radial Distribution Network

Table A.13: Line and bus data for the standard 69-bus network.

Line data					**Bus data**		
From	**To**	**R(Ω)**	**X(Ω)**	**busno**	**Busno**	**P(KW)**	**Q(kVar)**
1	2	0.0005	0.0012	1	1	0	0
2	3	0.0005	0.0012	2	2	0	0
3	4	0.0015	0.0036	3	3	0	0
4	5	0.0251	0.0294	4	4	0	0
5	6	0.366	0.1864	5	5	0	0
6	7	0.3811	0.1941	6	6	2.6	2.2
7	8	0.0922	0.047	7	7	40.4	30
8	9	0.0493	0.0251	8	8	75	54
9	10	0.819	0.2707	9	9	30	22
10	11	0.1872	0.0619	10	10	28	19
11	12	0.7114	0.2351	11	11	145	104
12	13	1.03	0.34	12	12	145	104
13	14	1.044	0.345	13	13	8	5
14	15	1.058	0.3496	14	14	8	5.5
15	16	0.1966	0.065	15	15	0	0
16	17	0.3744	0.1238	16	16	45.5	30
17	18	0.0047	0.0016	17	17	60	35
18	19	0.3276	0.1083	18	18	60	35
19	20	0.2106	0.069	19	19	0	0
20	21	0.3416	0.1129	20	20	1	0.6
21	22	0.014	0.0046	21	21	114	81
22	23	0.1591	0.0526	22	22	5	3.5
23	24	0.3463	0.1145	23	23	0	0
24	25	0.7488	0.2475	24	24	28	20
25	26	0.3089	0.1021	25	25	0	0
26	27	0.1732	0.0572	26	26	14	10
3	28	0.0044	0.0108	27	27	14	10
28	29	0.064	0.1565	28	28	26	18.6
29	30	0.3978	0.1315	29	29	26	18.6
30	31	0.0702	0.0232	30	30	0	0
31	32	0.351	0.116	31	31	0	0
32	33	0.839	0.2816	32	32	0	0
33	34	1.798	0.5646	33	33	14	10
34	35	1.474	0.4873	34	34	9.5	14
3	36	0.0044	0.0108	35	35	6	4
36	37	0.064	0.1565	36	36	26	18.55
37	38	0.1053	0.123	37	37	26	18.55
38	39	0.0304	0.0355	38	38	0	0
39	40	0.0018	0.0021	39	39	24	17
40	41	0.7283	0.8509	40	40	24	17
41	42	0.31	0.3623	41	41	1.2	1
42	43	0.041	0.0478	42	42	0	0
43	44	0.0092	0.0116	43	43	6	4.3
44	45	0.1089	0.1373	44	44	0	0
45	46	0.0009	0.0012	45	45	39.2	26.3
4	47	0.0034	0.0084	46	46	39.2	26.3
47	48	0.0851	0.2083	47	47	0	0

From	To	R(Ω)	X(Ω)	busno
48	49	0.2898	0.7091	48
49	50	0.0822	0.2011	49
8	51	0.0928	0.0473	50
51	52	0.3319	0.1114	51
9	53	0.174	0.0886	52
53	54	0.203	0.1034	53
54	55	0.2842	0.1447	54
55	56	0.2842	0.1433	55
56	57	1.59	0.5337	56
57	58	0.7837	0.263	57
58	59	0.3042	0.1006	58
59	60	0.3861	0.1172	59
60	61	0.5975	0.2585	60
61	62	0.0974	0.0496	61
62	63	0.145	0.0738	62
63	64	0.7105	0.3619	63
64	65	1.041	0.5302	64
11	66	0.2012	0.0611	65
66	67	0.0047	0.0014	66
12	68	0.7394	0.2444	67
68	69	0.0047	0.0016	68

System voltage is 11kv

Busno	P(KW)	Q(kVar)
48	79	56.4
49	384	274.5
50	384	274.5
51	40.5	28.3
52	3.6	2.7
53	4.35	3.5
54	26.4	19
55	24	17.2
56	0	0
57	0	0
58	0	0
59	100	72
60	0	0
61	1244	888
62	32	23
63	0	0
64	227	162
65	59	42
66	18	13
67	18	13
68	28	20
69	28	20

Appendix V: Backward Forward Sweep and Harmonic Power Flow MATLAB Codes

```
function [LSI1,LSI2,Vmb,VSIb,THDb,PTloss,QTloss,power_f_active,Pt]=pf_78(start,x) % for 78-bus
% replace pf_78 with pf_69 for the IEEE 69-bus network
condition=1;
 %while condition==1
    jj=condition;
  sample_number=jj;
 source1=source1';

 S_base=110000;   %(kVA)
 V_base=15; %(kV)
 Z_base=1000*(V_base^2)/(S_base);
 I_base=S_base/(sqrt(3)*V_base);
 if start==1
 for i=1:numel(x)/2
    bus_data(x(i),2)=bus_data(x(i),2)-x(i+(numel(x)/2));     % for Type 1 DGS
 %for Type2 DGs use: bus_data(x(i),3)=bus_data(x(i),3)-x(i+(numel(x)/2));
 %for Type 3 DGs use: bus_data(x(i),3)=bus_data(x(i),3)-x(i+round((numel(x)/2)));
 %bus_data(x(i),2)=bus_data(x(i),2)-x(i+round((numel(x)/2)));
```

```
end

end
demanded_P=bus_data(:,2)/S_base;
demanded_Q=bus_data(:,3)/S_base;
R=line_data(:,3)/Z_base;
X=line_data(:,4)/Z_base;
nbus=length(bus_data);
nline=length(line_data);
Pt=sum(bus_data(:,2));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%
BIBC=zeros(nbus-1,nline);
for i=1:nline
   BIBC(:,line_data(i,2))=BIBC(:,line_data(i,1));
   BIBC(line_data(i,5),line_data(i,2))=1;
end
BIBC(:,1)=[]; %BIBC Matrix

%% Initilize voltage
Vmb=ones(1,nbus);   %voltage magnitude(pu)
%VSIb=ones(nbus,1);
%% start iteration
delta=1;eps=0.00001;iter=0;
MAXiter=1000;
while delta > eps
iter=iter+1;
   if iter>MAXiter
      break;
   end

   for k=1:nbus
      Ibus(k,1)=(demanded_P(k)-sqrt(-1).*demanded_Q(k))./(conj(Vmb(k)));
   end
   Inode=BIBC*Ibus(2:end); % It gives out branch current

   V(1)=1;
   for k=1:length(line_data)
     V(line_data(k,2))=Vmb(line_data(k,1))-(R(k,1)+sqrt(-1)*X(k,1))*(Inode(line_data(k,5)));
   end
   delta=max(abs(V-Vmb));
   Vmb=V;
end
```

```
%% results

if start==0
   figure(1)
   plot(abs(Vmb),'--*b')
   ylabel('Voltage Magnitude (p.u.)')
   xlabel('Bus Number')
   title('Vlotage profile')
end

%% loss calculation
IL=Inode;
VSII(1)=1;
for k=1:length(line_data)
%     IL(k)=(V(line_data(k,1))-V(line_data(k,2)))/(R(k)+sqrt(-1).*X(k));
   S_line(k)=V(line_data(k,1))*conj(IL(k));
   PLoss(k)=R(k)*(abs(IL(k))^2)*S_base;
   QLoss(k)=X(k)*(abs(IL(k))^2)*S_base;
   VSII(line_data(k,2))=(abs(V(line_data(k,1))))^4-4*(demanded_P(k)*X(k)-
demanded_Q(k)*R(k))^2-
4*(demanded_P(k)*R(k)+demanded_Q(k)*X(k))*(abs(V(line_data(k,1))))^2;VSI=VSII;
end

power_f_active=real(S_line)*S_base;
power_f_reactive=imag(S_line)*S_base;
VSIb=VSII;
PTloss=sum(PLoss); % total active or reactive loss
QTloss=sum(QLoss);% total reactive loss

%%%%%%%%%%%%%%%% loss sensitivity index %%%%%%%%%%%%%
LSI1=-
2*((demanded_P(2:end)+PLoss'/S_base).^2+(demanded_Q(2:end)+QLoss'/S_base).^2).*(R(k,1).*
Z_base)./(abs(Vmb(1,2:end)).^3)';
% LSI1=-
2*(demanded_P(2:end).^2+demanded_Q(2:end).^2).*(R(k,1).*Z_base)./(abs(Vm(1,2:end)).^3)';
[Value1,Index1]=sort(LSI1);
Index1=Index1+1;
LSI1=[Value1,Index1];

LSI2=2*((demanded_Q(2:end)+QLoss'/S_base).^2).*(R(k,1).*Z_base)./(abs(Vmb(1,2:end)).^2)';
[Value2,Index2]=sort(LSI2,'descend');
Index2=Index2+1;
LSI2=[Value2,Index2];
```

```
%LSI1=VSIb';
%%%%%%  calculate the loads Impedance)

Z_loads=zeros(nbus,1);
for k=1:length(line_data)
    Z_loads(k,1)=V(line_data(k,1))/conj((demanded_P(k)+sqrt(-
1).*demanded_Q(k))/V(line_data(k,1)));
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%  harmonic load flow   %%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

h=1;
line_z=R+1j*X*h;
Z_loads_1=real(Z_loads)+1j*imag(Z_loads)*2*pi*50*h;
load_1=Z_loads_1';
%source1(size(IL))=0;

line_1=zeros(nbus-1,nline);
for k=1:length(line_data)
  line_1(k,k)=line_z(k,1);
end

V_bus=Vmb;
I_bus=Ibus;
V_bus_size=size(V_bus);
for mm=1:5
   if mm==1
      h=5;
      source=abs(source1(mm,:)).*I_bus';
   end
   if mm==2
      h=7;
      source=abs(source1(mm,:)).*I_bus';
   end
   if mm==3
      h=11;
      source=abs(source1(mm,:)).*I_bus';
   end
   if mm==4
      h=13;
      source=abs(source1(mm,:)).*I_bus';
   end
```

```
   if mm==5
      h=17;
      source=abs(source1(mm,:)).*I_bus';
   end



   line=(real(line_1)+1j*imag(line_1)*h);
   Z_loads=(real(Z_loads_1)+1j*imag(Z_loads_1)*h);
   load=Z_loads';



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
Size_line=size(line);
Size_load=size(load);
Size_source=size(source);

[line_number,xxx]=size(find(line~= 0));
[xxx,load_number]=size(find(load~= 0));
[xxx,source_number]=size(find(source~= 0));
parallel_number=source_number+load_number;

%%%%%%%%  for A   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

A=zeros(line_number,parallel_number);
A1=A;
load_number1=load_number;
source_number1=source_number;
for i=Size_line:-1:1
   for j=Size_line:-1:1
      if line(i,j)~= 0
         if source(1,j+1)~= 0
            A1(i,source_number1)=1;
            if source_number1 ~= 1
               source_number1=source_number1-1;
            end
         end
            if load(1,j+1)~= 0
               A1(i,load_number1+source_number)=1;
               load_number1=load_number1-1;
            end
      end
```

```
   end
end


for i=Size_line:-1:2
   for j=Size_line:-1:1
      if line(i,j)~= 0
        for k=1:Size_line
           if line(k,i-1)~= 0            %% means these 2 line are conected to each other
             for m=1:parallel_number
                if A1(j,m)~= 0
                  A1(i-1,m)=A1(j,m);
                end
             end
           end
        end
      end
   end
end

A=A1;

%%%%%%%%%%%%%%%%%%    for HA   %%%%%%%%%%%%%%%%%%%%%%%%

HA=zeros(line_number,parallel_number);
nn=0;
HA(1,:)=line(1,1);

for i=2:1:Size_line
   for j=1:1:Size_line
      if line(i,j)~= 0
        for k=1:Size_line
           if line(k,i-1)~= 0
             HA(j,:)=HA(i-1,:)+line(i,j)*A(j,:);
           end
        end
      end
   end
end


   HAss=1;
%%%%%%%%%%%%%%%%    for Zs and HLF   %%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
Zs=zeros(load_number);
i=1;

for n=1:Size_load(1,2)
   if load(1,n)~= 0
      Zs(i,i)=load(1,n);
      i=i+1;
   end
end

HLF=HAss+Zs;

%%%%%%%%%%%%%%%%%   finding currents of parallel elements  %%%%%%
Ih=zeros(source_number,1);
i=1;
HAsh=1;
for n=1:Size_source(1,2)
   if source(1,n)~= 0
      Ih(i,1)=source(1,n);
      i=i+1;
   end
end

Is= -HAsh.*Ih;

%%%%%%%%%%%%  Harmonic load flow    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%

I=zeros(parallel_number,1);
size_Ih=size(Ih);
size_Is=size(Is);
k=1;
for i=1:parallel_number
   if i<= size_Ih(1,1)
      I(i,1)=Ih(i,1);

   end
end

V_bus_h=HA*I;

 V_bus_h_size=size(V_bus_h);
 v_bus_h_shift=zeros(V_bus_h_size(1,1)+1,1);
 v_bus_h_shift(1,1)=0;
```

```
for i=2: V_bus_h_size(1,1)+1
   v_bus_h_shift(i,1)=V_bus_h(i-1,1);
end

 V_bus_h=v_bus_h_shift;

V_mag=abs(V_bus_h);
V_ang=angle(V_bus_h)*180/pi;
V_size=size(V_bus_h);
for i=1:V_size(1,1)
% fprintf('V%g=   %g , %g\n',i,V_mag(i,1),V_ang(i,1));
end

%%%%%%%%   injected current to each bus  %%%%%%%%%

for i=1:V_size(1,1)
   if source(1,i)~= 0
   I_harmonic_load(i,1)=V_bus_h(i,:)/Z_loads(i,1);
   else
   I_harmonic_load(i,1)=0;
   end
end
I_ingected=source'-I_harmonic_load;

if mm==1
   V_bus_h_total_abs_5th(jj,:)=abs(V_bus_h');
   I_ingected_total_abs_5th(jj,:)=abs(I_ingected');
end
if mm==2
   V_bus_h_total_abs_7th(jj,:)=abs(V_bus_h');
   I_ingected_total_abs_7th(jj,:)=abs(I_ingected');
end
if mm==3
   V_bus_h_total_abs_11th(jj,:)=abs(V_bus_h');
   I_ingected_total_abs_11th(jj,:)=abs(I_ingected');
end
if mm==4
   V_bus_h_total_abs_13th(jj,:)=abs(V_bus_h');
   I_ingected_total_abs_13th(jj,:)=abs(I_ingected');
end
if mm==5
   V_bus_h_total_abs_17th(jj,:)=abs(V_bus_h');
   I_ingected_total_abs_17th(jj,:)=abs(I_ingected');
end
```

```
V_bus_h_total(mm,:)=abs(V_bus_h');
I_ingected_total(jj+(mm-1)*sample_number,:)=abs(I_ingected');
end



V_bus_h_total(mm,:)=abs(V_bus_h');
I_ingected_total(mm,:)=abs(I_ingected');

%fprintf('sample No. %g for %gth harmonic generated.\n',jj,h);


THD1=sqrt(V_bus_h_total_abs_5th'.^2+V_bus_h_total_abs_7th'.^2+V_bus_h_total_abs_11th'.^
2+V_bus_h_total_abs_13th'.^2+V_bus_h_total_abs_17th'.^2)./abs(V_bus)';
THDb=sum(THD1)/length(V_bus);

%THD=sqrt(((V_bus_h_total_abs_5th)'.^2+(V_bus_h_total_abs_7th)'.^2+(V_bus_h_total_abs_11
th)'.^2+(V_bus_h_total_abs_13th)'.^2+(V_bus_h_total_abs_17th)'.^2))./abs(V_bus);
%thdt=sum(thd);
%THD=thdt/77;
%fprintf('   ****   All  done   ****.\n');

V_bus_h_total_abs=abs(V_bus_h_total);
I_ingected_h_total_abs=abs(I_ingected_total);

End
```

Appendix VI: Particle Swarm Optimization MATLAB Codes

```
clc
clear
close all
format short g


condition=1;
%while condition==1
   jj=condition;
   sample_number=jj;

%%%%%%%%%%% Uncompansated %%%%%%%%%%%%%%%%
start=0;
```

```
x=0;
[LSI1,LSI2,Vmb,VSIb,THDb,PTloss,QTloss,power_f_active,Pt]=pf_78(start,x);
disp(' ')
disp('=====================================================')
disp('Results of 78 bus system without DG unit')
disp(' ')
disp(['Total active loss is: ' num2str(PTloss) ' kW'])
disp(['Total reactive loss is: ' num2str(QTloss) ' kVar'])
[value_v,index_v]=sort(abs(Vmb));
disp(['Minimum voltage is: ' num2str(value_v(1)) ', at bus ' num2str(index_v(1))])
disp(['Maximum voltage is: ' num2str(value_v(end-1)) ', at bus ' num2str(index_v(end-1))])
[value_vsi,index_vsi]=sort(abs(VSIb));
disp(['Minimum VSI is: ' num2str(value_vsi(1)) ', at bus ' num2str(index_vsi(1))])
disp(['Maximum VSI is: ' num2str(value_vsi(end-1)) ', at bus ' num2str(index_vsi(end-1))])
disp(' ')
pause(0.5)

if start==0
  figure(2)
   plot(VSIb,'--*b')
   ylabel('Voltage stability index')
   xlabel('Bus Number')
   title('Voltage stability index')
end
%%%%%%%%%% after DG unit integration %%%%%%%%%%%%%%%%
start=1;

Ndg_max=3;
%% parameters setting
a=numel(LSI1(:,1))/2;
a=round(a);
lb=[LSI1(1:a,2)' 0*Pt*ones(1,a)]; % lower bound
ub=[LSI1(1:a,2)' 0.9*Pt*ones(1,a)];  % upper bound
nvar=2*a; % number of variable


NP=250;          % number particle
T=60;          % max of iteration

W=1;
C1=2;
C2=2;

alpha=0.05;
```

```
%% initialization
tic
empty.pos=[];
empty.cost=[];
empty.velocity=[];

particle=repmat(empty,NP,1);

for i=1:NP
particle(i).pos=lb+rand(1,nvar).*(ub-lb);
[particle(i).cost]=fitness(Ndg_max,particle(i).pos,start);
particle(i).velocity=0;
end

bparticle=particle;

[value,index]=min([particle.cost]);

gparticle=particle(index);

%% main loop

best=zeros(T,1);
AVR=zeros(T,1);

for t=1:T

    for i=1:NP

         particle(i).velocity=W*particle(i).velocity...
                   +C1*rand(1,nvar).*(bparticle(i).pos-particle(i).pos)...
                   +C2*rand(1,nvar).*(gparticle.pos-particle(i).pos);

        particle(i).pos=particle(i).pos+particle(i).velocity;

        particle(i).pos=min(particle(i).pos,ub);
        particle(i).pos=max(particle(i).pos,lb);


        [particle(i).cost]=fitness(Ndg_max,particle(i).pos,start);


        if particle(i).cost<bparticle(i).cost
```

```
            bparticle(i)=particle(i);

            if bparticle(i).cost<gparticle.cost
               gparticle=bparticle(i);
            end
         end



      end



 W=W*(1-alpha);

 best(t)=gparticle.cost;
 AVR(t)=mean([particle.cost]);

 disp([ ' t = ' num2str(t)   ' BEST = '  num2str(best(t))]);



end

%% results
disp('=====================================================================================================
===================================================================')
disp([' Buses are   =  '  num2str(gparticle.pos(1:a))])
disp([' sizes are   =  '  num2str(gparticle.pos(a+1:end))])

j=0;
for i=1:a
   if gparticle.pos(a+i)<150
   gparticle.pos(a+i)=0;
   else
   j=j+1;
   Buses(j)=gparticle.pos(i);
   Sizes(j)=gparticle.pos(a+i);
   end
end
   disp(' ')
   disp('     Buses       Size(kW) ')
   disp([Buses' Sizes'])
   disp(' ')
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
[LSI1,LSI2,Vm,VSI,THD,PTloss,QTloss,power_f_active]=pf_78(start,gparticle.pos);

figure(1)
hold on
plot(abs(Vm),'-r^')
legend('Before DG unit placed',' After DG unit placed')
xlim([1 78])

figure(2)
hold on
plot(VSI,'-r^')
legend('Before DG unit placed',' After DG unit placed')
xlim([1 78])

disp(' ')
disp('====================================================')
disp('Results of 78 bus system with DG unit')
disp(' ')
disp(['Total active loss is: ' num2str(PTloss) ' kW'])
disp(['Total reactive loss is: ' num2str(QTloss) ' kVar'])

[value_v,index_v]=sort(abs(Vm));
disp(['Minimum voltage is: ' num2str(value_v(1)) ', at bus ' num2str(index_v(1))])
disp(['Maximum voltage is: ' num2str(value_v(end-1)) ', at bus ' num2str(index_v(end-1))])
[value_vsi,index_vsi]=sort(abs(VSI));
disp(['Minimum VSI is: ' num2str(value_vsi(1)) ', at bus ' num2str(index_vsi(1))])
disp(['Maximum VSI is: ' num2str(value_vsi(end-1)) ', at bus ' num2str(index_vsi(end-1))])
disp(' ')

disp(' ')
   disp('   Vbus(before DG)   VSI(before DG)   Vbus(with DG)   VSI(with DG) ')
   disp([abs(Vmb') abs(VSIb') abs(Vm') abs(VSI')])
   disp(' ')

save PSO
```