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OPTIMAL PLACEMENT OF DISTRIBUTED GENERATION ON A POWER SYSTEM USING PARTICLE SWARM OPTIMIZATION

By

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in Electrical Engineering
in the Department of Electrical and Computer Engineering

Mississippi State, Mississippi

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In recent years, the power industry has experienced significant changes on the distribution power system primarily due to the implementation of smart-grid technology and the incremental implementation of distributed generation. Distributed Generation (DG) is simply defined as the decentralization of power plants by placing smaller generating units closer to the point of consumption, traditionally ten mega-watts or smaller. While DG is not a new concept, DG is gaining widespread interest primarily for the following reasons: increase in customer demand, advancements in technology, economics, deregulation, environmental and national security concerns.

The distribution power system traditionally has been designed for radial power flow, but with the introduction of DG, the power flow becomes bidirectional. As a result, conventional power analysis tools and techniques are not able to properly assess the impact of DG on the electrical system. The presence of DG on the distribution system creates an array of potential problems related to safety, stability, reliability and security of the electrical system. Distributed generation on a power system affects the voltages, power flow, short circuit currents, losses and other power system analysis results.

Whether the impact of the DG is positive or negative on the system will depend primarily on the location and size of the DG.

The objective of this research is to develop indices and an effective technique to evaluate the impact of distributed generation on a distribution power system and to employ the particle swarm optimization technique to determine the optimal placement and size of the DG unit with an emphasis on improving system reliability while minimizing the following system parameters: power losses, voltage deviation and fault current contributions. This research utilizes the following programs to help solve the optimal DG placement problem: Distribution System Simulator (DSS) and MATLAB.

The developed indices and PSO technique successfully solved the optimal DG sizing and placement problem for the IEEE 13-Node, 34-Node and 123-Node Test Cases. The multi-objective index proved to be computational efficient and accurately evaluated the impact of distributed generation on the power system. The results provided valuable information about the system response to single and multiple DG units.

DEDICATION

I dedicate this dissertation to my wife, Hillary, for her love and support throughout the years. I would like to also dedicate this dissertation to my mother and father who showed unconditional love and support towards me throughout my life. To my family and friends who encouraged me along the way.

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Power System

The power system consists of three main areas: generation, transmission and distribution. A traditional power system consists of a centralized power plant, a networked transmission grid and a radial distribution system. Generation is generally defined as the act of producing energy. Electricity is produced at a centralized generating station with the following primary energy resources: coal, hydro, natural gas, nuclear, and petroleum. These generation plants are usually located a long distance from the end users. Typically, transmission refers to the transportation of bulk energy along a long network of power lines. It is often intended to refer specifically to 115 kilo-volts of electricity or higher, but in some cases 30kV or higher are considered transmission level. Lastly, distribution refers to the process of transporting energy from high-voltage transmission networks to the end-user, the customer [1].

The U.S. power system is an aging infrastructure. With an estimated 25% increase in energy consumption by 2035 [2], the transmission power network is in need of major upgrades. Upgrades to the power system tend to encounter economic, environmental and political barriers. While these barriers present many challenges, power utilities still have the responsibility to provide safe and reliable power to the customer. Typically, power companies build large centralized power plants to accommodate an increase in energy consumption, but transporting the power across an aging and congested network threatens the security and stability of the power system. Less transmission capability means that more generation resources would be required [3]. Distributed generation (DG) is often used to offset transmission costs or other costs associated with major improvements to the power grid. When the costs and timing of building new lines are weighed against the costs of distributed generation, DG tends to be more economically attractive. Other alternatives such as capacitor placement, conductor upgrades, and feeder reconfiguration can also be instrumental in optimizing the power system, but DG tends to be more economical and provides additional benefits when compared to some of these alternatives [3].

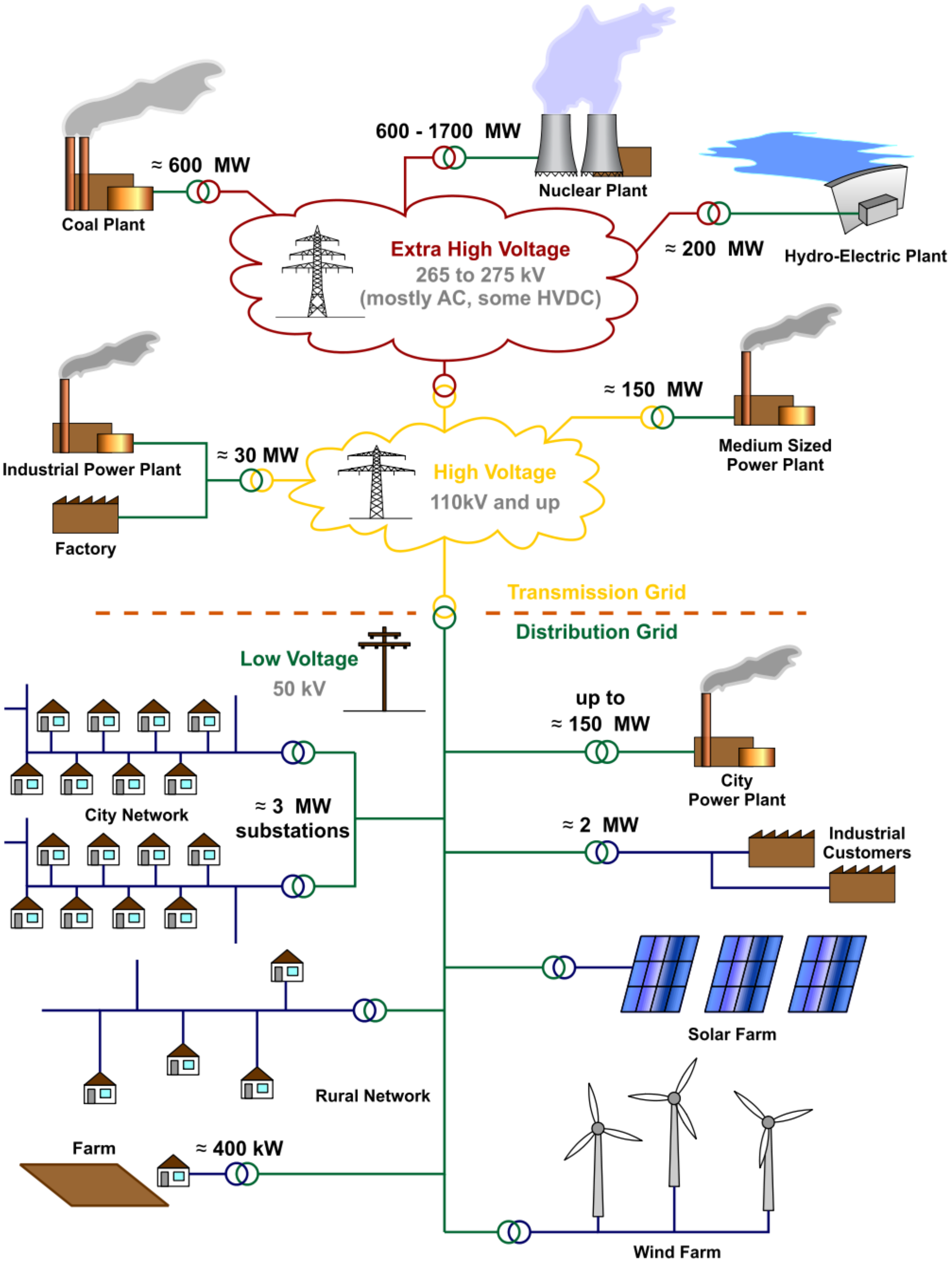


Figure 1.1 Three main components of a typical power system [7]

1.2 Introduction to Distributed Generations

In recent years, the power industry has experienced significant changes on the distribution power system primarily due to the implementation of smart-grid technology and the incremental implementation of distributed generation. Distributed Generation is simply defined as the decentralization of power plants by placing smaller generating units closer to the point of consumption, traditionally ten mega-watts or smaller [4]. While DG is not a new concept, DG is gaining widespread interest primarily for the following reasons: increase in customer demand, advancements in technology, economics, deregulation, environmental and national security concerns.

Distributed generation can be used in the following applications: industrial, commercial, residential or utility. Distributed generators can use either renewable or nonrenewable energy sources. The nonrenewable DG sources include, but are not limited to, fuel cells, diesel, micro-turbines or natural gas; while renewable DG sources include, but are not limited to, biomass, photovoltaic and wind. DG can be operated as a primary generator, standby generator, or a source for reactive power. The owners and operators of distributed generators can be placed into one of two categories: non-utility or utility.

There are two main types of generators: synchronous and induction. Synchronous and induction generators are typically interconnected to the utility. Synchronous generators have the capability to provide both real and reactive power to the system, while induction generators can provide real power, but need to receive reactive power from an external source [6].

The distribution power system traditionally has been designed for radial power flow, but with the introduction of DG, the power flow becomes bidirectional. As a result, conventional power analysis tools and techniques are not able to properly assess the impact of DG on the electrical system. The presence of DG on the distribution system creates an array of potential problems related to safety, stability, reliability and security of the electrical system. Distributed generation on a power system affects the voltages, power flow, short circuit currents, losses and other power system analysis techniques. Whether the DG has a positive or negative effect is dependent on its location and size.

1.3 Objective of Dissertation

Research efforts related to evaluating the impact of DG on the distribution power system have increased in recent years. One challenge in evaluating DG is to develop indices and techniques that properly assess the impact of DG on the system. The following system parameters are typically taken into consideration when evaluating the system response to DG: voltage profile, power losses, fault currents, system reliability, economics, load data, DG penetration level and line-capacity.

The objective of this research is to develop an effective methodology for evaluating the impact of distributed generation on an unbalanced distribution power system that consists of weighted-indices to properly assess the following system parameters: voltage deviation, fault current deviation, power losses and system reliability. These indices will be used in conjunction with the particle swarm algorithm to solve the optimal sizing and location of DG on the distribution power system to achieve that following:

- Develop practical indices that properly and accurately assess the impact of DG on a distribution power system
- Develop a more flexible and accurate method for solving the optimal DG sizing and placement problem
- Incorporate the use of the particle swarm algorithm to solve the DG sizing and location optimization problem using multiple assessment parameters

The proposed Distributed Generation Index (DGI) is formulated to capture the influence of DG on four major parameters in power system analysis: voltage, fault currents, power system losses and system reliability. The objective function is designed to maximize system reliability and minimize the voltage deviation, fault current deviation, and power system losses. The purpose of the multi-objective index is to help provide valuable insights concerning the impact of DG on various power system parameters. Finding the optimal size and location of DG is critical in maximizing the positive impacts of DG, while minimizing the negative impacts on the system.

1.4 Outline of Dissertation

The dissertation is organized in the following format:

Chapter 2 explores the literature review related to the optimal DG sizing and placement problem and the various optimization techniques used to assist in solving the optimization problem.

Chapter 3 introduces the problem statement and discusses the limitations of existing methods and the need for the development of an improved method.

Chapter 4 describes the formulation of the optimal DG sizing and placement problem using particle swarm optimization on an unbalanced distribution system. It provides the simulations results using Distribution System Simulator and MATLAB.

Chapter 5 illustrates the application of the newly formed DG sizing and placement optimization algorithm on the IEEE 13-Node, 34-Node and 123-Node test cases. Results are discussed and analyzed.

Chapter 6 summarizes research results and discusses future work.

1.5 REFERENCES

[1] Jack Casazza and Frank Delea, “Understanding Electric Power Systems: An Overview of the Technology and the Marketplace,” New Jersey, IEEE Press, 2003, p.1.

[2] U. S Department of Energy: [Online]: http://www.doe.gov

[3] "IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems," *IEEE Std 1547-2003*, pp. 0_1-16, 2003.

[4] Narain Hingorani and Laszlo Gyugyi, “Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems,” New York, IEEE Press, 2000, p.1.

[5] A. Lakshimi Devi and B. Subramanyam, "Optimal DG Unit Placement For Loss Reduction In Radial Distribution System-A Case Study," *ARPN Journal of Engineering and Applied Sciences*, vol. 2, December 2007.

[6] Charles J. Mozina, “A Tutorial on the Impact of Distributed Generation (DG) on Distribution Systems,” 61st Annual Conference for Protective Relay Engineers, April 2008.

[7] Wikipedia, “Electricity Grid Schematic English,” Image, http://en.wikipedia.org/wiki/File:Electricity_Grid_Schematic_English.svg.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Distributed Generation

The Public Utility Regulatory Policies Act of 1978, also known as PURPA, allows a consumer to install distributed generation on their property and interconnect to the power grid in such a way as to reduce their utility bill [1]. Utilities are allowed to set technical requirements, but are otherwise prohibited from discriminating against customers placing DG on the system. Since the federal law allows non-utility owned DG operators entrance into the power market, power companies have been presented with the tasks of designing a system to provide secure and reliable power to the consumers while accommodating distributed generation.

DG is expected to experience wide-spread implementation on the power system within the next several years due to advancements in technology, the process of deregulation and an increase in the cost of energy. These factors, along with others, have contributed leading to an increase in research activities to develop effective methodologies and techniques to properly assess and optimize distributed generation on the power system. The presence of DG on the distribution system creates an array of potential problems related to stability, reliability and security of the electrical system. The Institute of Electrical & Electronics Engineers (IEEE) has developed the IEEE Application Guide for IEEE Std 1547, IEEE Standard for Interconnecting Distributed

Resources with Electric Power Systems. The IEEE 1547 is primarily designed to address some of the following aspects of the impact of DG on the power system [27]:

- General Installation Requirements
- Voltage Regulation
- Power Quality
- Synchronization
- Islanding
- Safety

DG placement and sizing play a critical role when evaluating the overall performance of DG on a distribution system. Finding the optimal location and size of these generators can be instrumental in minimizing operating and maintenance cost, minimizing losses, maximizing power delivery, increasing reliability, increasing voltage stability and decreasing system design impact. In many applications, the generator is not able to be placed at the optimal or near optimal location due to the type of energy source, land restrictions, cost or other limiting factors.

2.2 Evaluating the Impact of DG on the Distribution Power System

The introduction of distributed generation on the power system affects the voltage, power flow, short circuit current, losses and other power system analysis results; therefore, it becomes imperative to provide the engineer with the necessary tools and techniques to properly assess the state of the system and to ensure that the power system operates within the specified design parameters. Many researchers [6, 8, 10, 11,] have developed analytical methods for evaluating the impact of DG on losses, power flow, protection schemes, voltage profiles and cost. Traditionally, mathematical optimization methods have been used to solve power system optimization problems. These solutions typically find the local optimum; therefore, artificial intelligence techniques have become popular in solving power system optimization problems to obtain a global or near global optimum solution [5].

2.2.1 DG Optimization Using Traditional Methods

Caisheng et al [8] proposed an analytical approach to determine the optimal location for DG in radial and networked system with an objective of loss minimization. In [7], Borges et al developed a methodology to evaluate the effects the DG location and capacity have on losses, reliability and voltage profile of the distribution networks. Chiradeja et al [10-11] developed indices focusing on voltage improvements, environmental impact reduction, and line-loss reduction that quantified the technical benefits of DG. Chiradeja concluded that the DG rating, location, and operating power factor are critical in reducing line losses. Ochoa el al [3] developed a multi-objective index to evaluate the impact of distributed generation on the distribution network. These indices focused on the following system parameters: losses, voltage, short circuit current, and capacity of conductors. These performance indices were combined to develop a comprehensive evaluation of the system parameters.

Griffin et al [16] have proposed an algorithm to determine the near optimal placement of fuel cell DG units with respect to system losses. Nazari et al [19] examined the effects of DG on power losses with a combination of uniform and lumped loads and developed a mathematical model of power loss reduction as a function of DG to determine the optimum DG placement and operating conditions. Mahat et al [24] solved for the optimal size and location of a wind turbine (DG) in a primary distribution system when minimizing power losses. The exact loss formula was used to calculate the power loss. Chaitusaney et al [9] developed equations that can be used to determine the proper size of the DG without violating the operating parameters of the existing protection scheme. The authors stated that the addition of DG changes the system characteristics from radial to a mesh- configuration, which results in a change in the over-current protection scheme. As a result, fuse blowing and false tripping are the most reported consequences of DG on existing protection schemes. Butler-Purry et al [20] analyzed the impact of DG on an over-current protection scheme by varying the size and location of the DG and observing the change in steady state normal and short circuit currents as well as the protection coordination.

Mendez et al [22] investigated impact of DG on power system losses. The authors used the Newton-Raphson algorithm to obtain active and reactive flows and their influence in total losses. The authors analyzed the effects of DG penetration level, DG dispersion, various DG technologies, and the different combinations of DG technologies on system losses. The authors concluded that the ability to control the reactive power output of the DG helps to decrease the overall power losses. Khoa et al [17] developed an algorithm using the primal dual interior point method to reduce line losses by solving for the optimal size and location of the DG on the distribution power system.

While the aforementioned methods provide insightful and useful techniques for evaluating the impacts of DG, these methods tend to be very difficult to implement, computational intensive and usually do not find the optimal solution.   To help eliminate some of these concerns, Baghzouz [6] developed “simple rules of thumbs” for evaluating the impact of DG on the following distribution feeder parameters: power flow, power loss, voltage regulation and fault currents. The author suggested that the general rules used for capacitor placement can also be used for DG placement and sizing to help minimize power losses under certain system conditions.

2.2.2 DG Optimization Using Artificial Intelligence

Since the distribution optimization problem consist of both continuous and discrete variables, many researchers have incorporated evolutionary methods to solve for the optimal operation because of independence of initial conditions, differentiability and continuity of the objective function [26]. Evolutionary algorithms have the capability of providing near optimal solutions regardless of the problem type [2]. Examples of some evolutionary techniques are genetic algorithms, tabu search, simulated annealing, particle swarm, ant colony, differential evolution and evolutionary strategies. Particle swarm optimization (PSO) will be used in this work to help solve the optimal DG placement and sizing problem.

Silvestri et al [21] used a genetic algorithm to determine the optimum location and size of the DG unit to minimize power losses in the system. Gandomkar et al [15] used a combination of genetic algorithm, tabu search, and/or simulated annealing to help determine the optimal location and size of DG to minimize power losses in a power network. Haesen et al [12] also used genetic algorithm to solve for the optimal location and size of two different DG applications, photovoltaic and combined heat and power, on a distribution power system with respect to minimizing losses while maintaining an acceptable voltage level. The authors used various load profiles and examined the different results. In [4], Devi et al used fuzzy logic to calculate a suitability index at each node to determine the optimal size and location and number of DG units to install on the distribution power system.

Niknam et al [26] compared various evolutionary methods (GA, ACO, PSO, Tabu Search, DE) for solving the problem of optimal operation in distribution networks with regard to the effect of DGs and concluded that ACO and PSO provided consisted, precise and better optimal solutions than the other methods. Krueasuk et al [23] evaluated the performance of particle swarm optimization algorithm when finding the optimal placement of various types of distributed generation in a primary distribution system with respect to minimizing power losses. The authors evaluated several DG types and their impact on power losses (i.e. photovoltaic, synchronous condenser, and induction generator). Using the backward and forward sweep to calculate the power flow, the authors used a standard equation to calculate losses on the 33 and 69 bus distribution test systems. The developed methodology proved to provide an acceptable solution when compared to a simple heuristic search method.

The aforementioned methods using particle swarm optimization for solving the DG size and placement optimization problem only used a single objective parameter (i.e. minimizing losses). In this work, a more effective methodology and set of DG indices will be developed to properly assess the impact of DG on the distribution power system and implemented in conjunction with the particle swarm algorithm to solve a weighted-multi-objective DG sizing and location optimization problem with an emphasis on minimizing the following system parameters: power losses, voltage deviation and fault current contributions.

2.3 Overview of Particle Swarm Optimization

Particle Swarm Optimization is a multipoint, population based search algorithm that was introduced by James Kennedy (social psychologist) and Russell Eberhart (EE) in

1995 [25]. The development of the particle swarm technique was inspired by observing the behavior of social organisms that live in large groups (i.e. birds or schools of fish). In recent years, particle swarm optimization (PSO) has become a very popular technique in solving non-linear optimization problems. Of the many types of evolutionary algorithms; particle swarm is preferred primarily because of its computational efficiency, simplicity and ability to avoid local optima. PSO has the following key advantages over other evolutionary optimization techniques [25]:

- Flexibility to integrate to form hybrid tool with other optimization techniques
- Less sensitive to the nature of the objective function (i.e. convex, continuous)
- Ability to escape local optima
- Simple to program and implement
- Converges with or without good initial conditions

Because of these advantages, Particle Swarm Optimization has been used in the following power systems related problems: Reactive Power Allocation [14], DG Placement [23], Optimal Power Flow [13], Capacitor Placement [5] and FACTS Placement [18].

The PSO algorithm consists of the following steps:

1) Randomly initialize particles' position and velocity vectors
2) Measure fitness of each particle and store the individual best ($pbest_i$)
3) Store the overall best fitness value of all particles (gbest)
4) Update velocity and position vectors according to equations 2.1 and 2.2 [Figure 2.1]
5) Repeat steps 2 -3 until termination criterion is meet (i.e. iterations, objective function)

The basic particle swarm algorithm can be found in the following form:

$$\begin{aligned} v_i^{new} = w_1 v_i &+ [c_1 * rand\,(\quad) * (pbest_i - p_i)] \\ &+ [c_2 * rand\,(\quad) * (gbest_i - p_i)] \end{aligned} \tag{2.1}$$

$$p_i^{new} = p_i + v_i^{new} \tag{2.2}$$

Where,

1) v_i^{new} is the updated velocity of particle i
2) v_i is the velocity of the particle i
3) $w_1$is the inertia weight coefficients
4) c_1 and c_2 are weight coefficients
5) $rand\,(\quad)$is a uniform random number between 0-1 (maintain diversity in search)
6) $pbest_i$is the best position of the particle i (local)
7) $p_i$is the position of the particle i
8) $gbest$ is the best position of the entire particle swarm (global)

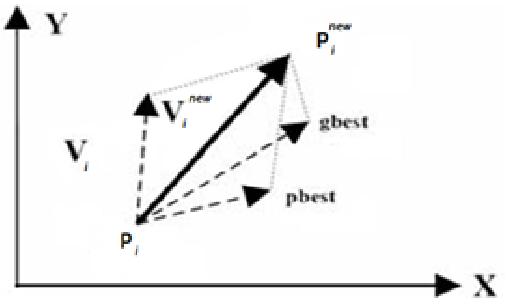


Figure 2.1 PSO Search Space Trajectory [25]

Each particle (agent) adjusts its position (solution) according to its own experiences and the experiences of other particles. The particles can communicate with other particles in close proximity or all the particles (global). In order to ensure that the particle remains in a feasible search region, velocity clamping is used to limit the movement of the particle.

$$v_{max} = k * p_{max} \tag{2.3}$$

1) v_{max} is the maximum value the particle can move when updating position
2) k is a user defined constriction factor
3) p_{max} is the maximum possible value of the particle

The particle swarm optimization algorithm can be separated in the following way:

1) Current velocity of the particle i $(w_1 v_i)$
2) Cognitive component of each individual particle i $[c_1 * rand(\ ) * (pbest_i - p_i)]$
3) Social component of each individual particle i $\left[c_2 * rand(\ ) * \left(gbest_i - p_i\right)\right]$

The inertia weight is designed to accelerate or decelerate the particle from its original trajectory. The inertia weight can range from$0 \leq w_1 \leq 1.2$, but is typically set between $.80 \leq w_1 \leq 1.2$. The cognitive component represents the ability of the particle to learn from its past experiences, while the social component allows the particle to learn for the experience of other particles (i.e. entire group). The coefficients, c_1 and c_2, can range from $0 \leq c_i \leq 2.0$, but are typically set between $1.2 \leq c_i \leq 2.0$. These coefficients determine whether the particle is learning more from itself (local search) or the entire swarm (global search). If the social and cognitive components are omitted, then the particles will move at the same speed in the same direction.

Particle swarm optimization is becoming very popular in terms of research topics and new applications. The original PSO model suffers from premature convergence when applied to multi-objective problems [2]. During the past few years, researchers have studied various aspects of the algorithm by evaluating the effects of the parameters, studying the trajectories of the particles and investigating the various types of communication methods of the algorithm. These research efforts have resulted in the formulation of improved versions of particle swarm optimization that addresses the convergence problem along with other issues related to the performance of the particle swarm algorithm [25].

2.4 Summary

This chapter provides an overview of the optimal DG sizing and placement problem. It reviews existing indices and methods used to solve the optimal DG sizing and placement problem. It also evaluates both traditional and artificial intelligent techniques used to help solve the DG sizing and placement problem and provides an overview of Particle Swarm Optimization.

2.5 REFERENCES

[1] U. S Department of Energy: [Online]: http://www.doe.gov

[2] P. Dutta, A. K. Sinha, N. Mawandia, and D. Chakraborty, "Comparison of Some Evolutionary Algorithms for Optimal Power Flow.”

[3] L. F. Ochoa, A. Padilha-Feltrin, and G. P. Harrison, "Evaluating distributed generation impacts with a multiobjective index," *IEEE Transactions on Power Delivery,* vol. 21, pp. 1452-1458, 2006.

[4] A. Lakshimi Devi and B. Subramanyam, "Optimal DG Unit Placement For Loss Reduction In Radial Distribution System-A Case Study," *ARPN Journal of Engineering and Applied Sciences,* vol. 2, December 2007.

[5] M. F. AlHajri, M. R. AlRashidi, and M. E. El-Hawary, "A Novel Discrete Particle Swarm Optimization Algorithm for Optimal Capacitor Placement and Sizing," *Electrical and Computer Engineering, 2007. CCECE 2007. Canadian Conference on*, 2007, pp. 1286-1289.

[6] Y. Baghzouz, "General rules for distributed generation - feeder interaction," Proceedings of *2006. IEEE Power Engineering Society General Meeting,* 2006, p. 4 pp.

[7] C. L. T. Borges and D. M. Falcao, "Impact of distributed generation allocation and sizing on reliability, losses and voltage profile," *Power Tech Conference Proceedings, 2003 IEEE Bologna,* 2003, p. 5 pp. Vol.2.

[8] W. Caisheng and M. H. Nehrir, "Analytical approaches for optimal placement of distributed generation sources in power systems," *IEEE Transactions on Power Systems,* vol. 19, pp. 2068-2076, 2004.

[9] S. Chaitusaney and A. Yokoyama, "Impact of protection coordination on sizes of several distributed generation sources," 2005 *Power Engineering Conference, IPEC 2005. The 7th International,* 2005, pp. 669-674 Vol. 2.

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

[11] P. Chiradeja and R. Ramakumar, "An approach to quantify the technical benefits of distributed generation," *IEEE Transaction on Energy Conversion,* vol. 19, pp. 764-773, 2004.

[12] M. E. Edwin Haesen, Bert Pluymers, Ivan Goethals, Vu Van Thong, Johan Driesen, Ronnie Belmans, Bart De Moor, "Optimal Placement and Sizing of Distributed

Generator Units Using Genetic Optimization Algorithms," *Journal of Electrical power Quality and Utilisation,* vol. 11, 2005.

[13] A. A. A. Esmin and G. Lambert-Torres, "Loss Power Minimization Using Particle Swarm Optimization," in *Neural Networks, 2006. IJCNN '06. International Joint Conference on*, 2006, pp. 1988-1992.

[14] Y. Fukuyama, "Comparative Studies of Particle Swarm Optimization Techniques for Reactive Power Allocation Planning in Power Systems," *Electrical Engineering in Japan,* vol. 153, 2005.

[15] M. Gandomkar, M. Vakilian, and M. Ehsan, "A combination of genetic algorithm and simulated annealing for optimal DG allocation in distribution networks," in *Electrical and Computer Engineering, 2005. Canadian Conference on*, 2005, pp. 645-648.

[16] T. Griffin, K. Tomsovic, D. Secrest, and A. A. L. A. Law, "Placement of dispersed generation systems for reduced losses," in *System Sciences, 2000. Proceedings of the 33rd Annual Hawaii International Conference on*, 2000, p. 9 pp.

[17] T. Q. D. Khoa, P. T. T. Binh, and H. B. Tran, "Optimizing Location and Sizing of Distributed Generation in Distribution Systems," in *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES,* 2006, pp. 725-732.

[18] M. Saravanan, S. M. R. Slochanal, P Veenkatesh, and J. P. S. Abraham, "Application of Particle Swarm Optimization Technique for Optimal Location of FACTS devices considering Cost of Installation and System Loadability," *Electric Power Systems Research,* vol. 77, pp. 276-283, 2007.

[19] M. H. Nazari and M. Parniani, "Determining and Optimizing Power Loss Reduction in Distribution Feeders due to Distributed Generation," in *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES*, 2006, pp. 1914-1918.

[20] J. A. Silva, H. B. Funmilayo, and K. L. Bulter-Purry, "Impact of Distributed Generation on the IEEE 34 Node Radial Test Feeder with Overcurrent Protection," in *Power Symposium, 2007. NAPS '07. 39th North American*, 2007, pp. 49-57.

[21] A. Silvestri, A. Berizzi, and S. Buonanno, "Distributed generation planning using genetic algorithms," in *Electric Power Engineering, 1999. PowerTech Budapest 99. International Conference on*, 1999, p. 257.

[22] V. H. Mendez, J. Rivier, J. I. de la Fuente, T. Gomez, J. Arceluz, and J. Martin, "Impact of Distributed Generation on Distribution Losses," in *Proceedings of the 3rd Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion,* Athens Greece, 2002.

[23] Wichit Krueasuk and W. Ongsakul, "Optimal Placement of Distributed Generation Using Particle Swarm Optimization," in *Proceedings of the 2006 Australasian Universities Power Engineering Conference*, Victoria, Australia, 2006.

[24] Pukar Mahat, Weerakorn Ongsakul, and N. Mithulananthan, "Optimal Placement of Wind Turbine DG in Primary Distribution Systems for Real Loss Reduction," *ESD2006* Phuket, Thailand, 2006.

[25] R. Poli, J. Kennedy, and T. Blackwell, "Particle Swarm Optimization: An Overview," *Swarm Intell*, vol. 1, pp. 33-57, 2007.

[26] T. Niknam, A. M. Ranjbar, A. R. Shirani, B. A. M. B. Mozafari, and A. A. O. A. Ostadi, "Optimal operation of distribution system with regard to distributed generation: a comparison of evolutionary methods," in *Industry Applications Conference, 2005. Fourtieth IAS Annual Meeting. Conference Record of the 2005*, 2005, pp. 2690-2697 Vol. 4.

[27] "IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems," *IEEE Std 1547.2-2008*, 2009.

CHAPTER 3

EVALUATION OF THE OPTIMAL SIZING & PLACEMENT OF THE DISTRIBUTED GENERATION PROBLEM

This chapter describes the DG sizing and optimization problem, briefly discusses the limitations of existing distributed generation optimization methods and techniques, and describes the simulation tools used in the research.

3.1 Introduction to Distributed Generation Optimization

In power systems, developing techniques and methods to optimize the performance of the system is critical in providing safe and reliable power to the customer in a cost efficient manner. Unfortunately, the power transmission system has not been updated properly to accommodate the growth in electricity demand in many regions of the United States. With limited and congested transmission access, distributed generation has become a viable solution to the many challenges facing the power industry. However, before connecting a DG to the electric power grid, it is critical to do analysis of the impact of the DG to the power system.

Optimal Power Flow is a tool in the power industry that allows the users to analyze the state of power system parameters. Power flow results give vital information about the voltages, angles, currents and power losses of the system. Typically in a distribution power system, the power flows in one direction, from the source to the loads; however, when a DG is introduced to the system, the distribution system resembles a network system where power flow is bi-directional. Bi-directional power flow presents many challenges for conventional power distribution system analysis. Also, analyzing an unbalanced distribution system tends to be more complex than a balanced system. The power system is subject to a variety of constraints in order to maintain a safe and reliable system.

3.2 Limitation of Existing DG Optimization Methods and Techniques

Many techniques and methods have been developed to solve the optimal sizing and placement of distributed generation. While these techniques have yielded good results, many are iteration based approaches that only use a single system parameter to optimize the problem. Some of the techniques that use a multi-objective function use computational intensive methods to evaluate the impact of distributed generation. Others use environmental indices, for example, which have the tendency to have subjective and complicated variables; therefore, making it difficult to accurately assess the impact of DG on a given distribution system.

Some research efforts incorporate artificial intelligent approaches to solve the optimal DG sizing and placement problem. In many of these cases, only one system parameter is used to solve the problem and this may provide the solution to reach a local optimum instead of the global optimum.

3.3 Proposed Work

In evaluating DG on a distribution power system, DG placement and sizing are critical factors in minimizing power losses, minimizing voltage deviation, minimizing fault current deviation, minimizing operating and maintenance costs, and maximizing power delivery and reliability; thereby, increasing the overall economic value of the system. Quantifying the technical impact of DG on a distribution power system consists of developing indices that emphasize the system response to DG. These indices should reflect both the positive and negative impacts of DG by taking a combination of the following factors into consideration: voltage profile, power losses, fault currents, system reliability, economic, load data, DG penetration level and line-capacity.

The goal of this research is to develop an effective methodology for evaluating the impact of distributed generation on an unbalanced distribution power system that consists of weighted-indices that properly evaluate the following system parameters: power losses, voltage deviation and fault current deviations. These indices will be used in conjunction with the particle swarm algorithm to solve the optimal sizing and location of DG on the distribution power system. The IEEE Distribution Test Cases will be used to demonstrate the results of the weighted indices method.

3.4 Software Packages

In this research, the following software packages will be used: Distribution System Simulator (DSS) [13] and MATLAB [14]. The power flow results will be used in conjunction with the particle swarm algorithm to solve for the optimal size and placement of the DG. DSS in conjunction with MATLAB will be used to generate the power flow results while solving the DG optimal sizing and placement problem. The author also used MATLAB as the programming language to develop the particle swarm algorithm.

3.4.1 MATLAB

MATLAB is a “Matrix Laboratory” primarily developed to provide a user-friendly environment for working with matrices. MATLAB is a dynamic simulation environment used to perform numerical analysis on an array of engineering and mathematical problems. MATLAB provides a convenient and flexible programming platform to solve complex optimization problems. Since MATLAB has the capability of interfacing with other programming languages, MATLAB will be used in conjunction with DSS to solve the optimal DG placement problem using the particle swarm algorithm.

3.4.2 Distribution System Simulator (DSS)

Distribution System Simulator (DSS or OpenDSS) is an Object Pascal based program, with a sparse matrix solver written in C and C++. Since DSS is an open source code, it is often referenced as OpenDSS. DSS provides a flexible programming platform for performing distribution power system analysis. The program is implemented as a stand-alone executable program and a Component Object Model Dynamically Linked Library (COM DLL) that can be interfaced with various external programs. DSS is a general purpose frequency-domain simulation tool that was primarily designed to perform distributed generation analysis on a distribution power system, specifically harmonic analysis [13].

The distribution software analysis package is capable of performing analysis on balanced or unbalanced systems that are operated on a radial or networked configuration. DSS is able to handle multiple DGs on the system at a given time, modeling various types of load and power system components. DSS also has the ability to calculate the per-phase voltage drop, power flow, fault current calculations, power system losses and other power system parameters. DSS models both synchronous and induction generators. DSS has been used to implement on some of the following problems: Wind Plant Simulations, Harmonics and Inter-harmonic Analysis, Distributed Generation

Interconnection Analysis, Neutral-to-Earth Voltage Simulations and the development of the IEEE Distribution Test Feeder Cases [13].

OpenDSS is capable of being implemented through the COM interface using programs like MATLAB, MS Office Visual Basics, Python or other programming languages. The user is able to drive the entire OpenDSS simulation through the COM interface using the text-base command interface and as well as other available functions and user generated scripts as seen in Figure 3.1. The results may be written in a Comma-separated Value (CSV) format.

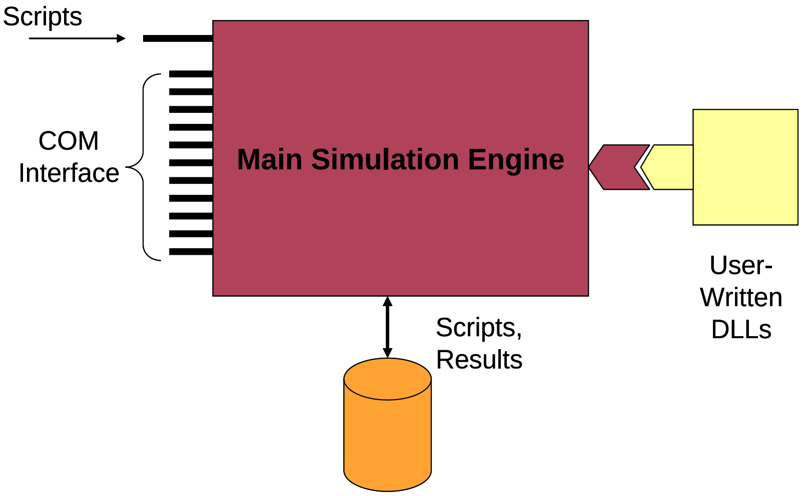
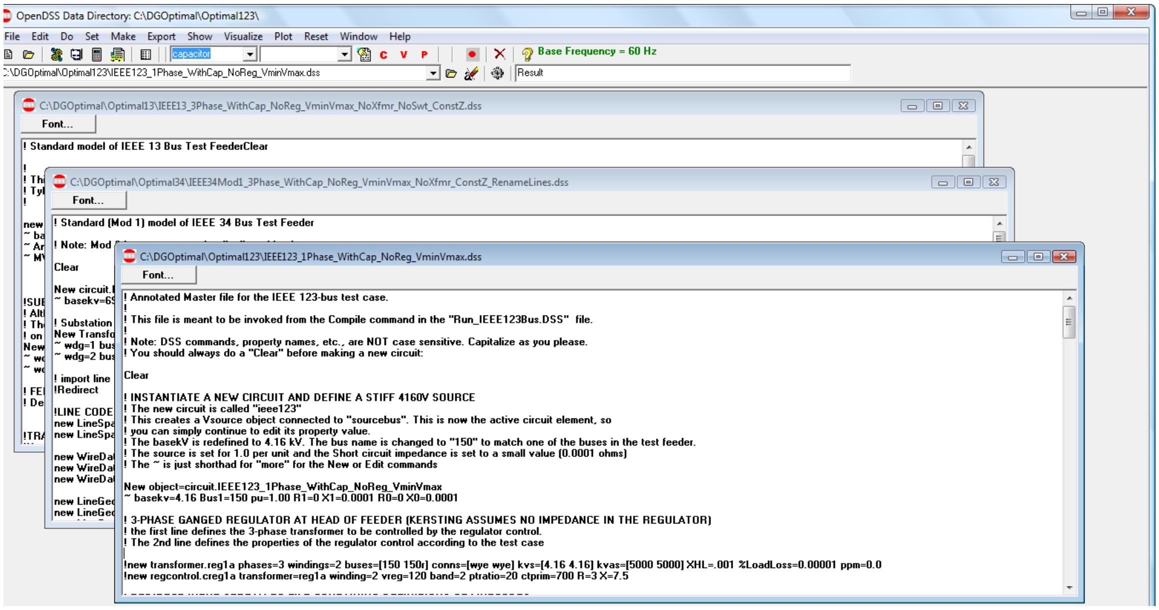


Figure 3.1 DSS Structure [13]



```
! Standard model of IEEE 13 Bus Test FeederClear
```

```
! Standard (Mod 1) model of IEEE 34 Bus Test Feeder
```

```
! Annotated Master file for the IEEE 123-bus test case.
!
! This file is meant to be invoked from the Compile command in the "Run_IEEE123Bus.DSS"  file.
!
! Note: DSS commands, property names, etc., are NOT case sensitive. Capitalize as you please.
! You should always do a "Clear" before making a new circuit:

Clear

! INSTANTIATE A NEW CIRCUIT AND DEFINE A STIFF 4160V SOURCE
! The new circuit is called "ieee123"
! This creates a Vsource object connected to "sourcebus". This is now the active circuit element, so
! you can simply continue to edit its property value.
! The basekV is redefined to 4.16 kV. The bus name is changed to "150" to match one of the buses in the test feeder.
! The source is set for 1.0 per unit and the Short circuit impedance is set to a small value (0.0001 ohms)
! The ~ is just shorthad for "more" for the New or Edit commands

New object=circuit.IEEE123_1Phase_WithCap_NoReg_VminVmax
~ basekv=4.16 Bus1=150 pu=1.00 R1=0 X1=0.0001 R0=0 X0=0.0001

! 3-PHASE GANGED REGULATOR AT HEAD OF FEEDER (KERSTING ASSUMES NO IMPEDANCE IN THE REGULATOR)
! the first line defines the 3-phase transformer to be controlled by the regulator control.
! The 2nd line defines the properties of the regulator control according to the test case

!new transformer.reg1a phases=3 windings=2 buses=[150 150r] conns=[wye wye] kvs=[4.16 4.16] kvas=[5000 5000] XHL=.001 %LoadLoss=0.00001 ppm=0.0
!new regcontrol.creg1a transformer=reg1a winding=2 vreg=120 band=2 ptratio=20 ctprim=700 R=3 X=7.5
```

Figure 3.2 DSS programming code for modeling the IEEE Test Cases

The core of the OpenDSS program structure is written in Delphi Code and generates the primitive Y matrix for each element in the modeled system. The program begins the iteration process after creating the system Y-matrix and performing a zero load power flow to obtain the initial voltages. The next voltage guess is obtained after adding the injection currents from all the power conversion elements in the circuit to the Iinj vector as seen in Figure 3.3. This process repeats until the system converges [13].

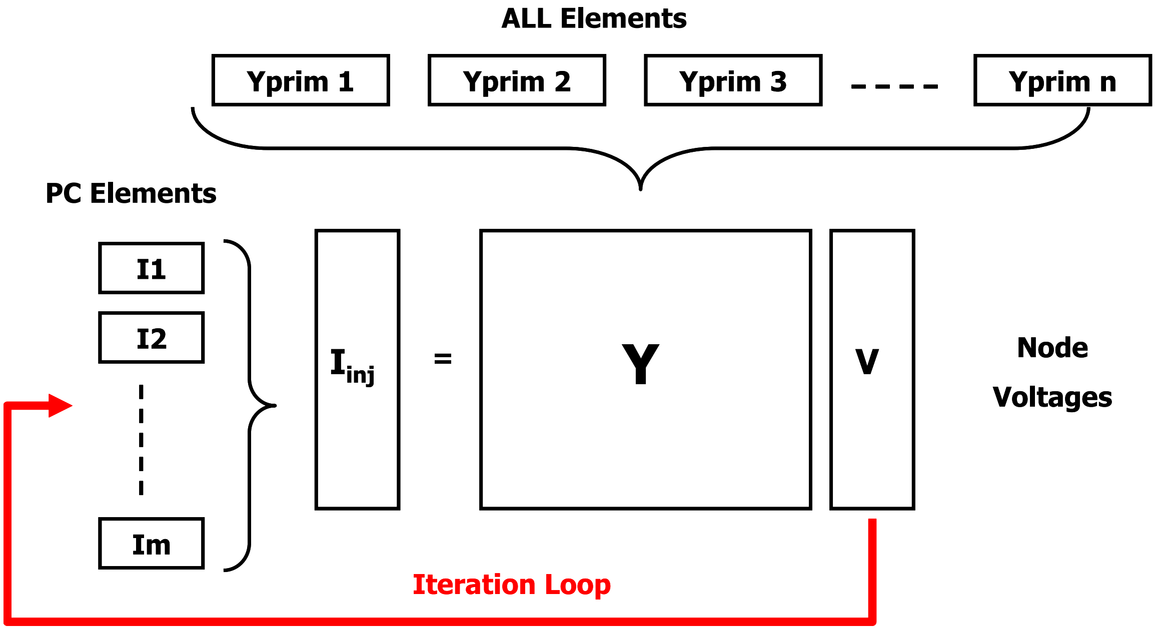


Figure 3.3 DSS Solution Loop [13]

3.5 Summary

This chapter introduced the Optimal DG sizing and placement problem and discussed limitation of existing methods. This chapter also discussed the simulation tools used in this research. Chapter 4 will elaborate on the formulation of the problem equations and describe the test systems used in this research.

3.6 REFERENCES

[1] L. F. Ochoa, A. Padilha-Feltrin, and G. P. Harrison, "Evaluating distributed generation impacts with a multiobjective index," *IEEE Transactions on Power Delivery,* , vol. 21, pp. 1452-1458, 2006.

[2] A. Lakshimi Devi and B. Subramanyam, "Optimal DG Unit Placement For Loss Reduction In Radial Distribution System-A Case Study," *ARPN Journal of Engineering and Applied Sciences,* vol. 2, December 2007.

[3] Y. Baghzouz, "General rules for distributed generation - feeder interaction," *Proceedings of the Power Engineering Society General Meeting, 2006. IEEE*, 2006, p. 4 pp.

[4] C. L. T. Borges and D. M. Falcao, "Impact of distributed generation allocation and sizing on reliability, losses and voltage profile," *Power Tech Conference Proceedings, 2003 IEEE Bologna*, 2003, p. 5 pp. Vol.2.

[5] W. Caisheng and M. H. Nehrir, "Analytical approaches for optimal placement of distributed generation sources in power systems," *IEEE Transactions on Power Systems,* , vol. 19, pp. 2068-2076, 2004.

[6] S. Chaitusaney and A. Yokoyama, "Impact of protection coordination on sizes of several distributed generation sources," *2005. IPEC 2005. The 7th International Power Engineering Conference,* , 2005, pp. 669-674 Vol. 2.

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

[8] P. Chiradeja and R. Ramakumar, "An approach to quantify the technical benefits of distributed generation," *IEEE Transaction on Energy Conversion,* , vol. 19, pp. 764-773, 2004.

[9] T. Griffin, K. Tomsovic, D. Secrest, and A. A. L. A. Law, "Placement of dispersed generation systems for reduced losses," *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences, 2000.*, 2000, p. 9 pp.

[10] T. Q. D. Khoa, P. T. T. Binh, and H. B. Tran, "Optimizing Location and Sizing of Distributed Generation in Distribution Systems," in *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES*, 2006, pp. 725-732.

[11] M. H. Nazari and M. Parniani, "Determining and Optimizing Power Loss Reduction in Distribution Feeders due to Distributed Generation," in *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES*, 2006, pp. 1914-1918.

[12] J. A. Silva, H. B. Funmilayo, and K. L. Bulter-Purry, "Impact of Distributed Generation on the IEEE 34 Node Radial Test Feeder with Overcurrent Protection," in *Power Symposium, 2007. NAPS '07. 39th North American*, 2007, pp. 49-57.

[13] Roger Dugan, “Reference Guide: The Open Distribution System Simulator (OpenDSS),” Electric Power Research Institute, 2009. (Need more information)

[14] “MATLAB Documentation” [Online] http://www.mathworks.com

CHAPTER 4

OPTIMAL DISTRIBUTED GENERATION SIZING & PLACEMENT PROBLEM FORMULATION

4.1 Problem Formulation

In evaluating the impact of DG on a distribution power system, the placement and sizing of the DG have a tremendous impact on power losses, voltage levels, fault current levels, operating cost, and reliability. Finding the optimal distributed generator sizing and placement is a complex problem with many variables to take into consideration. The scope of the problem depends mainly on the size of the distribution system and the number of possible DG configurations. The main components of a typical distribution power system primarily are lines, cables, transformer, regulators, switches, capacitors and load. Each power component has unique characteristics and responds according to certain system conditions. To evaluate a distribution system, the power components on the system must be properly modeled in an analysis software package. In this research, Distribution System Simulator will be used to analyze the test cases.

Quantifying the technical impact of DG on a distribution power system consists of developing indices that evaluate the system response to DG. These indices should reflect both the positive and negative impact of DG by taking a combination of system parameters into consideration: voltage profile, power system losses, fault currents, system reliability, load data and DG penetration level. Understanding the impact of DG on power system parameters can help determine the overall economic value of DG to the power system.

This chapter discusses the formulation of the optimal distributed generation sizing and placement problem. The purpose of this research is to develop an effective methodology for evaluating the impact of distributed generation on an unbalanced distribution power system that consists of weighted-indices that assess the following system parameters: power losses, voltage deviation, fault current deviations and system reliability. These indices will be used in conjunction with the particle swarm algorithm to solve the optimal sizing and location of DG on a distribution power system. In this research, a three phase synchronous generator will be used to determine the optimal size and placement problem.

4.2 System Constraints

The power system is designed to operate within certain system constraints. These constraints are design to ensure safe and reliable operation of the power system. In order to obtain practical results, the multi-objective DG sizing and location problem is subject to the following constraints:

1) Power Flow

$$P_{source} + P_{DG} - P_{Load} - P_{Loss} = 0 \tag{4.1}$$

$$Q_{source} + Q_{DG} - Q_{Load} - Q_{Loss} = 0 \tag{4.2}$$

$$V_{min}^{i} \le V_i \le V_{max}^{i} \tag{4.3}$$

2) Distributed Generator Constraints

$$P_{\ DGmin} \le P_{\ nDG} \le P_{\ DGmax} \tag{4.4}$$

$$Q_{\ DGmin} \le Q_{\ nDG} \le Q_{\ DGmax} \tag{4.5}$$

$$pf_{DGmin} \leq pf_{nDG} \leq pf_{DGmax} \tag{4.6}$$

Where, P_{source} = Total Active Power Supplied by Main Source

P_{DG} = Total Active Power Supplied by DG

P_{Load} = Total Active System Load Demand

P_{Loss} = Total Active System Losses

Q_{source} = Total Reactive Power Supplied by Main Source

Q_{DG} = Total Reactive Power Supplied by DG

Q_{Load} = Total Reactive System Load Demand

Q_{Loss} = Total Reactive System Losses

P_{nDG} = DG Active Power for n^{th}DG location

Q_{nDG} = DG Reactive Power for n^{th}DG location

pf_{nDG} = DG Power Factor for n^{th}DG location

4.3 Objective Function

The purpose of the multi-objective function is to provide valuable insight concerning the impact of DG on various power system parameters. The proposed Distributed Generation Index is formulated to capture the influence of DG on several major parameters in power system analysis: voltage, fault current, losses and system reliability. The objective function is designed to minimize the voltage deviation, fault current deviation, power losses and system interruption to customers. Finding the optimal size and location of DG is critical in maximizing the positive impacts of DG, while minimizing the negative impacts of DG on the system.

$$DGI_n^i = \left\{w_1\, VDI_n^i \;+\; w_2\, FCI_n^i \;+\; w_3\, LI_n^i + w_4\, RI_n^i\right\} \tag{4.7}$$

Where, DGI_n^i = Distributed Generation Index for n^{th}DG location and i^{th}DG size

VDI_n^i = Voltage Deviation Index for n^{th}DG location and i^{th}DG size

FCI_n^i = Fault Current Index for n^{th}DG location and i^{th}DG size

LI_n^i = Power System Loss Index for n^{th}DG location and i^{th}DG size

RI_n^i = Reliability Index for n^{th}DG location and i^{th}DG size

w_i = Weight Factors used to select evaluation criteria

n = DG location

i = DG size

Where, $\sum_{i=1}^{4} w_i = 1 \, \forall \, w_i \in [0,1]$

Since many power systems have unique features, the weight-factors provide the engineer with the ability to address specific concerns associated with a particular power system. In this research, the weight factors are selected to reflect typical evaluation metrics used in distribution analysis. The objective value closest to zero suggests that the size and location associated with that particular system configuration and simulation parameters provides the best overall system performance results.

4.3.1 Voltage Deviation Index

A typical distribution power system is unidirectional, where the power flows from the source to the point of consumption. When current flows through the conductors over a certain distance, the circuit experience voltage drop due to the relationship between voltage, current flow and the impedance of the conductors. The power system is designed to operate within certain voltage constraints, typically ± 5% of the base voltage under normal system conditions. Excessive voltage deviation can lead to power outages, equipment failure and power quality issues. The power utility typically utilizes voltage regulators and capacitor banks to regulate the voltage profile of the system to ensure that the voltage remain within a standard range of operations.

The implementation of DG on a power system alters the power flow; consequently, impacting the voltage profile of the system. One of the major benefits of DG on the power network is the ability to provide voltage support to the system. The size and location of the DG can result in over-voltage or under-voltage conditions. Since voltage decreases with respect to distance, a generator placed farther from the main source typically provides better voltage support to the system. The following index was developed in an effort to quantify the impact of the distributed generator on the overall voltage profile of the system:

$$\begin{Bmatrix} if \quad V\Phi_m > 0\,, VD\Phi_m = \ |V\Phi_m - 1| \\ else \ VD\Phi_m = 0 \end{Bmatrix} \tag{4.8}$$

$$NVD_m = \sum_{\Phi=1}^{3} VD\Phi_m \tag{4.9}$$

$$VDI_n^i = \frac{\sum_{m=1}^{k} NVD_m}{3} \tag{4.10}$$

Where, VDI_n^i = Voltage Deviation Index for n^{th}DG location and i^{th}DG size

$V\Phi_m$ = Per unit voltage of Φ phase at m node

$VD\Phi_m$ = Absolute value of per unit voltage deviation of Φ phase at m node

NVD_m = Sum of voltage deviation of Φ phase at m node

m = Node number

k = Total number of nodes

Φ = Phase number of conductor

The voltage deviation index is a simple method of analyzing the voltage profile for each DG size and location. The index is designed to be a single digit representation of the overall voltage profile for each DG configuration. This index is designed to provide a simple snapshot of how much the voltage deviates from the nominal voltage level. Since many circuits on a power system are single or double phase circuits, the index is design to only calculate the deviation for existing phases. The number closest to zero represents the best voltage profile with minimum overall deviation; in other words, the higher the index value, the more the overall voltage profile deviated from the nominal voltage level for a particular DG configuration.

4.3.2 Fault Current Index

A fault is an abnormal condition that occurs on an electrical system. Most faults on the power system are temporary and beyond the control of the utility engineer. In power systems, a typical fault is caused by inclement weather, equipment failure, vehicle accidents and other similar events. There are five general types of faults: three-phase, double-phase, single-phase-to-ground, double-phase-to-ground and three-phase-to-ground. Distribution systems have a combination of single, double and three phase circuits throughout the network. The majority of the faults on the system are single-line-ground faults. A protection scheme is implemented to ensure that the power system is capable of preventing or mitigated undesirable fault conditions on the network. A protection scheme can consist of the following equipment: protective relay, fuse, recloser, sectionalizer, switch and circuit breaker.

Protective Relaying is the aspect of power engineering that is primarily concerned with minimizing damage to equipment and service interruption under fault conditions.

When a major change occurs on the network, the protection scheme must maintain its integrity to ensure the delivery of safe and reliable power to the consumer. A relay is designed to cause the prompt removal of any element of a power system that operates in an abnormal manner that might cause damage or otherwise interfere with the effective operation of the rest of the system. Protection schemes and equipment ratings are adversely affected by increased fault current levels in the system. A drastic change in fault currents can result in equipment failure, false tripping, mis-operation of devices or a re-design of the protection scheme. Depending on the rated size and location, the installation of the DG can create potential problems with the existing protection scheme.

The short circuit currents (fault currents) can be calculated when performing the power flow analysis of a given power system. In analyzing the impact of DG on the system fault currents, the single phase-to-ground (SPG) fault type was used to calculate the following Fault Current Index:

$$FCI_n^i = \frac{\sum_{s=1}^{L} \left| \frac{SPG_{DG_s} - SPG_{Base_s}}{\max\left(SPG_{DG_s}, SPG_{Base_s}\right)} \right|}{L} \tag{4.11}$$

Where, FCI_n^i = Fault Current Index for n^{th}DG location and i^{th}DG size

SPG_{DG_s} = Line Section Single Phase - to -Ground Fault Current with DG

SPG_{Base_s} = Line Section Single Phase -to - Ground Fault Current without DG

s = Line section

L = Total number of line sections

The Fault Current Index (FCI) is a simple method that is used to evaluate the overall impact that DG has on existing fault current levels throughout the system. Given the fault current levels of a specific DG size and location, the FCI will calculate the average deviation between the fault current levels without DG to the fault current levels with DG for each line section. The FCI is a single digit representation of the average SPG deviation for a particular DG configuration. This number provides a snapshot of how much the fault current levels with DG deviates from the fault current levels without DG for the entire system. The value closest to zero represents the configuration that had the least impact on the existing fault current levels throughout the system.

Typically, the fault current contribution is proportional to the size of the generator; therefore, a large generator will provide the most current deviation from the base case fault current. If the FCI is the only parameter used to determine the optimal DG size and location, then the algorithm will select the smallest available DG size as the optimal value and/or the DG configuration that results in fault current levels similar to the base case values. Due to this characteristic, the Fault Index is intended to be utilized as a supplemental index.

4.3.3 Losses Index

The size and location of DG affects the system losses. Losses are proportional to the amount of current flowing through the conductors over a given distance.

$$P_{kWLoss_i} = \sum_{i=1}^{L} I^2 R \tag{4.12}$$

$$P_{kVarLoss_i} = \sum_{i=1}^{L} I^2 X \tag{4.13}$$

Where, P_{kWLoss_i} = Active Power Losses for i^{th} line section

$P_{kVarLoss_i}$ = Reactive Power Losses for i^{th} line section

I = Current in i^{th} line section

R = Resistive Component of line impedance

X = Reactive Component of line impedance

L = Total number of line sections

When a DG is placed closer to the point of consumption, the current travels a shorter distance; thereby, decreasing the overall system power losses. One can generally state that as the DG size increases, the overall system losses decreases. Occasionally, this assumption may vary under certain system conditions due to reverse power flow caused by the introduction of DG. The Loss Index calculates the ratio between the total system losses with DG and the total system losses without DG (base case) for each DG size and location. Apparent power losses will be used to calculate the following Loss Index:

$$BasekVALoss_0 = \sqrt{{BasekWLoss_0}^2 + {BasekVARLoss_0}^2} \tag{4.14}$$

$$DGkVALoss_n^i = \sqrt{{DGkWLoss_n^i}^2 + {DGkVARLoss_n^i}^2} \tag{4.15}$$

$$LI_n^i = \frac{DGkVALoss_n^i}{BasekVALoss_0} \tag{4.16}$$

Where, LI_n^i = Power System Loss Index for n^{th}DG location and i^{th}DG size

$BasekWLoss_0$ = Base Case Active Power System Losses

$BasekVARLoss_0$ = Base Case Reactive Power System Losses

$BasekVALoss_0$ = Base Case Apparent Power System Losses

$DGkWLoss_n^i$ = Active Power System Losses for n^{th}DG location and i^{th}DG size

$DGkVARLoss_n^i$ = Reactive Power System Losses for n^{th}DG location and i^{th}DG size

$DGkVALoss_n^i$ = Apparent Power System Losses for n^{th}DG location and i^{th} DG size

n = DG location

i = DG size

Where, LI_n^i<1, Total system losses decreased with DG indicates a positive impact.

LI_n^i = 1, Total system losses did not change with DG indicates a neutral impact.

LI_n^i> 1, Total system losses increased with DG indicates a negative impact.

4.3.4 Reliability Index

The primary responsibility of a distribution utility company is to ensure the delivery of safe and reliable power to the customer. Power system reliability can be generally described as the ability for the utility company to deliver electricity to the customer within acceptable standards while meeting the power demand of the customer. Under fault conditions, the system experiences temporary power interruptions to the customer. When such interruptions occur on the system, the utility is responsible for restoring the power to the customer in a safe and timely manner.

In an effort to create a standard reliability measurement system, the power industry developed various benchmark reliability indices as stated in the IEEE Guide for Electric Power Distribution Reliability Indices, IEEE Standard 1366 [1]. The reliability standard is designed to provide industry guidance for uniform practices on calculating consistent reliability indices. The standard measures reliability based on some of the following parameters:

1) Frequency of interruptions
2) Duration of interruptions
3) Number of customers
4) Amount of Power interrupted
5) Amount of Load

The following are three of the most commonly used reliability indices:

1) System Average Interruption Frequency Index (SAIFI)

   SAIFI indicates the how often the average customer experiences a sustained interruption over a predefined period of time.

$$SAIFI = \frac{\sum Total\ Number\ of\ Customers\ Interrupted}{Total\ Number\ of\ Customers\ Served} \tag{4.17}$$

2) System Average Interruption Duration Index (SAIDI)

   SAIDI indicates the total duration of interruption for the average customer during a predefined period of time (i.e. hours or minutes).

$$SAIDI = \frac{\sum Customer\ Interruption\ Durations}{Total\ Number\ of\ Customers\ Served} \tag{4.18}$$

3) Customer Average Interruption Duration Index (CAIDI)

   CAIDI indicates the average time required to restore service per sustained interruption.

$$CAIDI = \frac{\sum Customer\ Interruption\ Duration}{Total\ Number\ of\ Customers\ Interrupted} \tag{4.19}$$

The aforementioned reliability indices are calculated base on sustained interruptions. The test systems that are used in this research do not contain the information necessary to calculate these reliability indices. In an effort to include system reliability as a component of the multi-objective optimal DG placement and sizing problem, a modified version of the following load based reliability index will be used:

1) Average System Interruption Frequency Index (ASIFI)

   ASIFI is primarily used in industrial/commercial customer applications where there are few customers, but a large load concentration.

$$ASIFI = \frac{\sum Total\ Connected\ kVA\ of\ Load\ Interrupted}{Total\ Connected\ kVA\ Served} \tag{4.20}$$

2) Modified Average System Interruption Frequency Index (MASIFI)

$$MASIFI = \frac{\sum Total\ Connected\ kW\ of\ Load\ Interrupted}{Total\ Connected\ kW\ Served} \tag{4.21}$$

In this research, the ASIFI equation was slightly modified to include the active power (kW) instead of apparent power (kVA). The following equations will be used to develop the Reliability Index:

$$TLoadkW - DGTotalkW - TLoadkWInt = 0 \tag{4.22}$$

$$\frac{DGTotalkW}{TLoadkW} + \frac{TLoadkWInt}{TLoadkW} = 1 \tag{4.23}$$

$$RI_n^i = MASIFI_n^i = 1 - \frac{DGTotalkW_n}{TLoadkW_0} \tag{4.24}$$

Where, RI_n^i = Reliability Index for n^{th}DG location and i^{th}DG size

$DGTotalkW_n$ = Total DG Active Power for n^{th}DG location

$TLoadkW$ = Total Connected kW Served

$TLoadkWInt$ = Total Connected kW of Load Interrupted Served

The reliability index is based on total connected load and the capacity of the DG. If the RI is the only parameter used to determine the optimal DG size and location, then the algorithm will select the largest available DG size as the optimal value in order to minimize the reliability index. In this scenario, the location of the DG becomes irrelevant. Since the scope of this research does not focus on dynamic system reconfiguration, the reliability index is intended to be used as a supplemental index in the optimal DG sizing and placement problem. The index is based on the following assumptions and system conditions:

1) The main power source is assumed to be disconnected from the system
2) The system can be reconfigured such that $P_{DG} = P_{Load}$ to allow the DG to serve all connected load (Intentional islanding conditions)

The MASIFI has a range of zero to one. A higher value indicates poor reliability, while zero is an indication of good system reliability. The introduction of DG on the distribution system creates an opportunity for the utility company to improved system reliability by having an additional power source to supply the demand in the event that the main source is disconnected from the system. In Figure 4.1, for example, if the main source is disconnected from the main feeder under fault conditions at SW1, the MASIFI = $\frac{800\ kW}{800\ kW}$ = 1. In the same fault scenario with DG installed on the system, as shown in Figure 4.2, the MASIFI = $\frac{0\ kW}{800\ kW}$ = 0 or $MASIFI = 1 - \frac{800\ kW}{800\ kW} = 0$

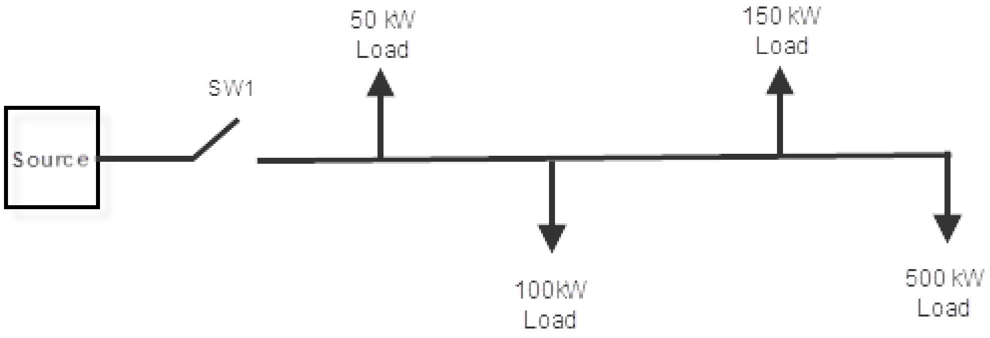


Figure 4.1 Single Line Diagram of Distribution Feeder without DG

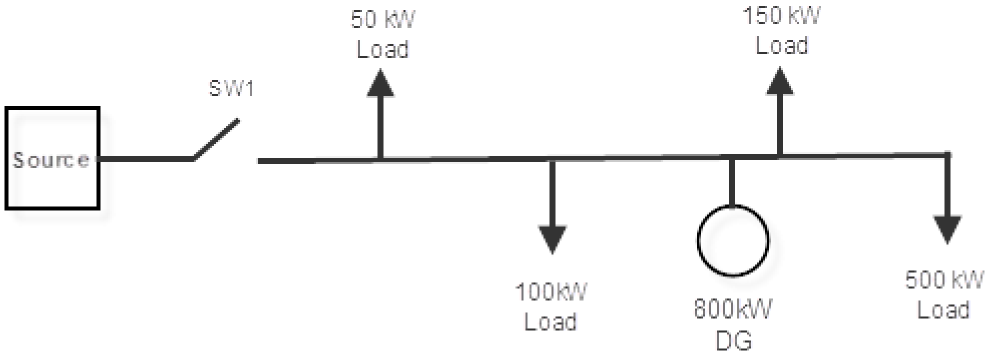


Figure 4.2 Single Line Diagram of Distribution Feeder with DG

4.4 Test Systems

The IEEE 13, IEEE 34 and IEEE 123 Distribution Test Cases will be used to conduct this research [2]. These are standard academic test cases for conducting research on a distribution power system. Each test case represent some unique characteristics that will allow a proper evaluate of the adaptability and scalability of the DG optimal sizing and placement algorithm.

4.4.1 IEEE 13-Node Feeder

The IEEE 13 Node Distribution Feeder is relatively small, but highly loaded with a nominal voltage of 4.16 kV. The IEEE 13 system provides the opportunity to examine the impact of DG on a condensed distribution system. The IEEE Distribution Test Cases consists of both unbalanced spot and distributed loads. The test case was slightly modified in order to properly evaluate the impact of DG on the various power system parameters. The following assumptions and modification were made:

1) The in-line transformer was removed from the circuits in order to have one feeder voltage level and to increase the number of possible generator locations.
2) All voltage regulators were removed from the test system to properly evaluate the impact of DG on the voltage profile.
3) The switch was not utilized in the simulation and was removed from the system.
4) Capacitors remained in the system for voltage minimum support.
5) All loads were converted to constant impedance models prior to running simulation.
6) Added additional node 670 ("Between" 632-671) to properly account for distributed load.

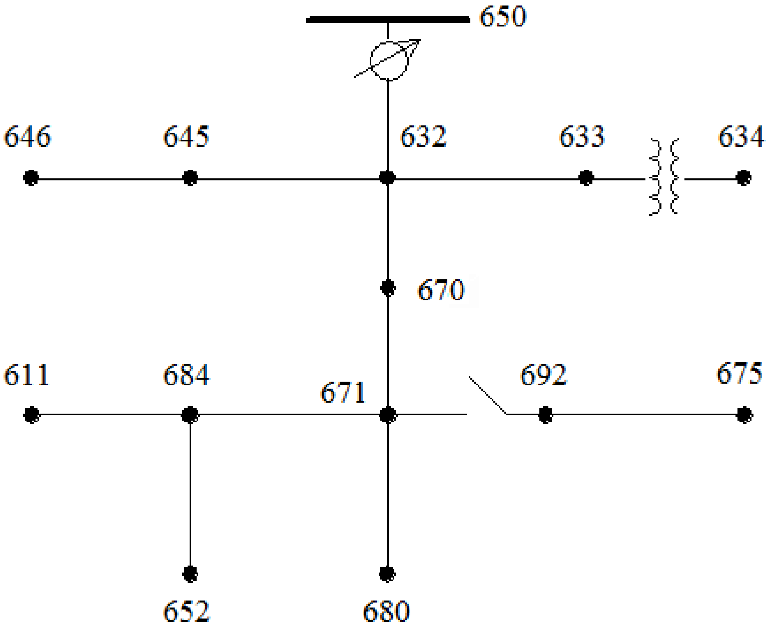


Figure 4.3 Single Line Diagram of the IEEE 13-Node Test System [2]

4.4.2 IEEE 34-Node Feeder

The IEEE 34 Node Distribution Feeder is an actual feeder in Arizona with a nominal voltage of 24.9 kV. The IEEE 34 test system is long and lightly loaded. Since the majority of the system load is located farther away from the substation, the IEEE 34 system provides an opportunity to examine the impact of DG on a “rural” distribution system. The test case was slightly modified in order to properly evaluate the impact of DG on the various power system parameters. The following assumptions and modification were made:

1) The in-line transformers were removed from the circuits in order to have one voltage level for the generator and to increase the number of possible generator locations.
2) All voltage regulators were removed from the test system to properly evaluate the impact of DG on the voltage profile.
3) Capacitors remained in the system for voltage minimum support.
4) All loads were converted to constant impedance models prior to running simulation.

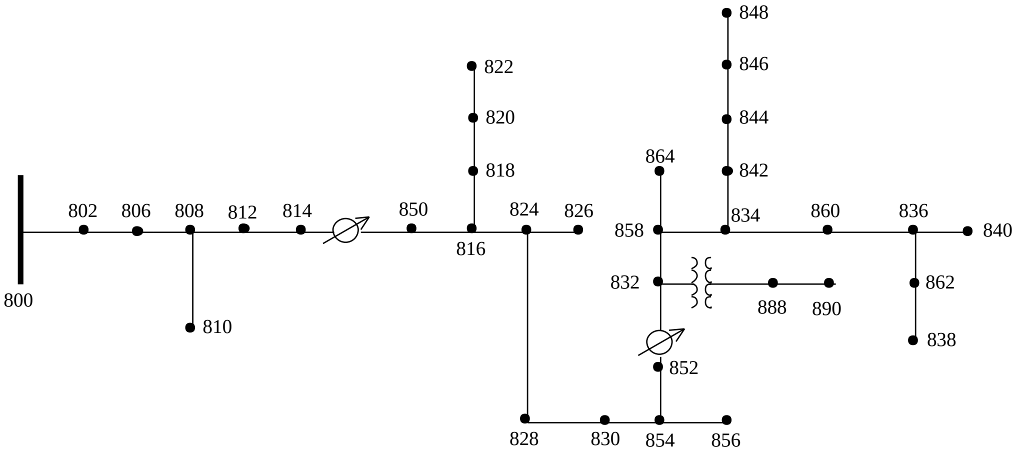


Figure 4.4 Single Line Diagram of the IEEE 34-Node Test System [2]

4.4.3 IEEE 123-Node Feeder

The IEEE 123 Node Distribution Feeder is relatively large with modest system loading and a nominal voltage of 4.16 kV. The IEEE Distribution Test Cases consists of both unbalanced spot and distributed loads. The test cases were slightly modified in order to properly evaluate the impact of DG on the various power system parameters. The following assumptions and modification were made:

1) All voltage regulators were removed from the test system to properly evaluate the impact of DG on the voltage profile.
2) Capacitors remained in the system for minimum voltage support.
3) All loads were converted to constant impedance models prior to running simulation.

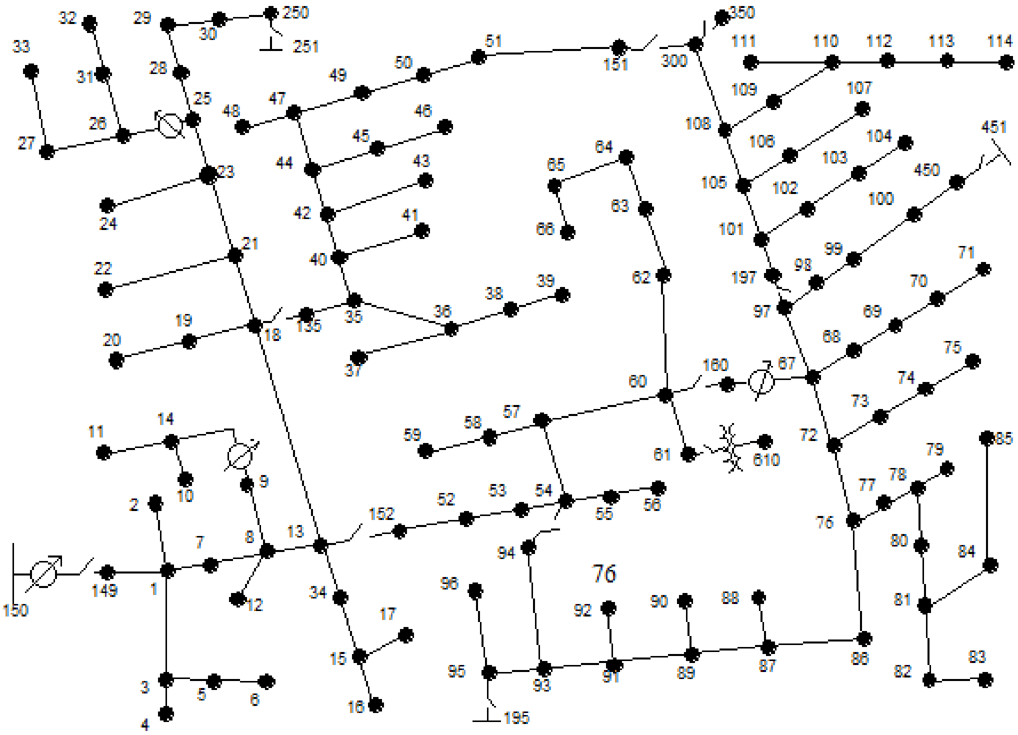


Figure 4.5 Single Line Diagram of the IEEE 123-Node Test System [2]

4.4.4 IEEE Test Cases Modifications

The test cases were slightly modified in order to properly evaluate the impact of DG on the various power system parameters. Since the voltage regulators were removed from the test system, the system encountered low voltage conditions that contributed to convergence issues during the simulation. During the simulation, if voltage levels fall below the range of the load and generators models, DSS converts all models to constant impedance to increase the probability of a successful convergence. Due to the possible changes in the load and generator model during the simulation, all load and generator models were converted to constant impedance models prior to the simulation in order to minimize variations in the results.

4.5 Analytical Optimal DG Approach

The rule of thumb associated with optimal capacitor bank sizing and placement is sometimes used as a guide to solve the optimal DG sizing and placement problem. This relationship is based on the functional and operational similarities that DG and capacitors have on the distribution power system. DG and capacitors are both capable of providing the following system improvements:

1) Improving Voltage Profile
2) System Loss Reduction
3) Improving Power Factor

The “2/3 Rule” is often applied for capacitor bank sizing and placement for losses and voltage impact studies on a distribution system. This rule of thumb was primarily developed for uniform loading application and has the following generalized equation:

$$CapSize_n = \frac{2}{2N + 1} \tag{4.25}$$

$$CapLoc_n = \frac{2}{2N + 1} * n \tag{4.26}$$

Where, $CapSize_n$ = Size of n^{th} capacitor

$CapLoc_n$ = Distance of n^{th} capacitor from main source

N = Total number of proposed capacitor banks to install

n = n^{th} capacitor bank

For example, the optimal sizing and placement for one capacitor banks on a typical uniform distribution feeder will be the following:

$$CapSize_1 = CapLoc_1 = \frac{2}{(2 * 1) + 1} = \frac{2}{3} \tag{4.27}$$

- Size: 2/3 * Total kVAR load
- Location: 2/3 * Distance from the main source

Where, the optimal sizing and placement for two capacitor banks on a typical uniform distribution feeder will be the following:

$$CapSize_1 = CapLoc_1 = \frac{2}{(2 * 2) + 1} = \frac{2}{5} \tag{4.28}$$

$$CapSize_2 = \frac{2}{(2 * 2) + 1} = \frac{2}{5} \tag{4.29}$$

$$CapLoc_2 = \frac{2}{(2 * 2) + 1} * 2 = \frac{4}{5} \tag{4.30}$$

- $CapSize_1$ = $CapSize_2$ = 2/5 * Total kVar load
- $CapLoc_1$ = 2/5 * Distance from the main source
- $CapLoc_2$ = 4/5 * Distance from the main source

In this research, the “2/3 Rule” was slightly modified to better approximate the optimal DG size and location for the weighted multi-objective based approach and utilized in the optimal DG algorithm to help improve the simulation results. Using the “2/3 Rule” for the optimal DG optimization problem with result in similar numerical calculations, but will use total active power (kW) to determine the size of the DG, instead of the total reactive power (kVAR).

$$MRTSize_n = \left\{w_1 \frac{2}{2N\ + .25} + w_2 \frac{1}{2N\ + 3} + w_3 \frac{1}{N\ + .1} + w_4 \frac{1}{N\ + .1}\right\} * \frac{\sqrt{N}}{(n + \ .1)} \tag{4.31}$$

Where, $MRTSize_n$ = Modified Rule of Thumb Size calculation for n^{th}number of DG

N = Total number of proposed DGs to install

w_i = Weight Factors used to select evaluation criteria

n = n^{th} number of DG

Where, $\sum_{i=1}^{4} w_i \ = 1 \ \forall \ w_i \ \in [0,1]$

4.6 Summary

This chapter describes the formulation of the optimal DG sizing and placement problem. The optimal DG sizing and placement program is formulated as a minimization problem. The development of the multi-objective distributed generation index was discussed. The DGI is sum of the following indices: voltage deviation, fault current deviation, losses and system reliability. Also, the development of the modified rule of thumb was also presented and discussed.

4.7 REFERENCES

[1] "IEEE Guide for Electric Power Distribution Reliability Indices," *IEEE Std 1366-2003,* 2003.

[2] W. H. Kersting, "Radial distribution test feeders," in *Power Engineering Society Winter Meeting, 2001. IEEE*, 2001, pp. 908-912 vol. 2.

CHAPTER 5

OPTIMAL DISTRIBUTED GENERATION SIZING & PLACEMENT ALGORITHM

5.1 Introduction

In Chapter 4, a new multi-objective distributed generation index was developed based on increasing system reliability, minimizing voltage deviation, system losses and fault current deviation. The proposed index is used in conjunction with the particle swarm optimization technique to solve the optimal DG sizing and placement problem. This chapter will analyze the performance of the proposed index and methodology on the IEEE 13-Node, 34-Node and 123-Node Test Cases. The test systems will be used to test the accuracy, speed, scalability, and adaptability of the optimal DG sizing and placement algorithm.

This research is conducted using the following software packages: Distribution Simulator Software and MATLAB. DSS is used to model the power system components and to obtain the steady state power flow solution. The optimal DG algorithm is written in MATLAB. The two software packages are interfaced to facilitate data exchange to obtain the information necessary to solve the optimal DG sizing and placement problem.

DSS has the capability of interfacing with external programs using the Component Object Modeling (COM) interface. This interface allows the user to control and operate DSS functions in an external programming environment. The DSS program has an internal control dispatching process implemented as a queue of action requests at specified times. DSS uses the following method to issue internal control commands [1]:

1) Populates control queue after successful convergence
2) Polls active control objects in the circuit
3) Push Control Action onto control queue (if changes are needed)
4) Pops the control actions to DoPendingAction (control handler) function at the time of execution

DSS allows the external program to simulate a DoPendingAction function through the COM interface. The external program can send commands to DSS using the text interface or the CktElement interface [1].

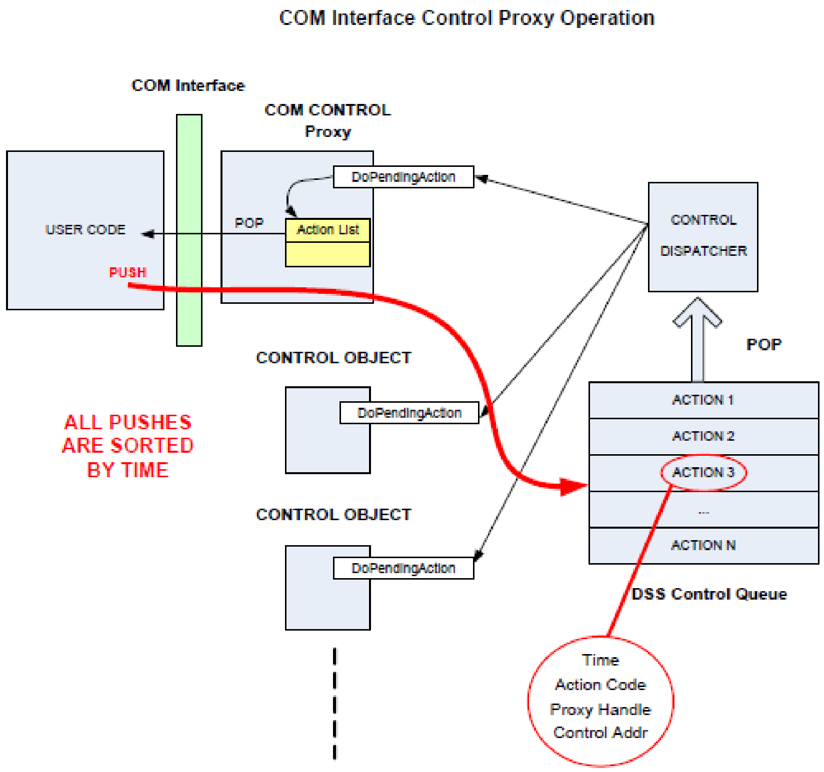


Figure 5.1 DSS COM Interface Diagram [1]

5.2 DSS Power Flow Solution

DSS is designed to solve small to medium sized distribution system. DSS is capable of providing power flow solutions for radial and networked distribution power systems. DSS can operate in the following modes: Snapshot mode, Daily mode, Duty-cycle Mode, or Monte Carlo mode. For this research, Snapshot mode will be used to obtain the voltage profile, system losses, current flows and other system information from the power flow solution. The solution mode must be switched to Fault Study Mode to obtain standard fault data. The two basic power flow solution types are [1]:

1) Iterative power flow
2) Direct solution

Loads and generators are power conversion elements. For the iterative power flow, loads and distributed generators are treated as injection sources. The generator is modeled as a negative load. In the Direct solution, loads and generators are included as admittances in the system admittance matrix, which is then solved directly without iterating.

There are two iterative power flow algorithms currently employed:

1) "Normal" current injection mode
2) "Newton" mode.

The Normal mode tends to be faster, but the Newton mode tends to be more robust in order to solve ill conditioned system. DSS has the following standard load modeling options:

1) Conventional constant P, Q load model.
2) Constant Impedance. P and Q vary by the square of the voltage.
3) Constant Power. Q is modeled as a constant reactance.
4) Constant Current. P and Q vary linearly with voltage magnitude.

5) Constant Power. Q is a fixed value independent of time.

5.3 Distributed Generator Model

The majority of distributed generator applications use two types of generators: induction or synchronous. Synchronous generations have the capability of providing reactive power to the system for voltage support. This research will use the built-in synchronous generator modeled in DSS. The generator is a simple single-mass model. The generator will be modeled as a Const Z to minimize variations in the simulation results due to possible low voltage conditions. DSS has the following standard generator modeling options:

1) Constant kW & specified power factor.
2) Constant Z.
3) Constant kW & Constant kV.
4) Constant kW. Fixed kVAR.

Table 5.1 Synchronous Generator Settings

Variable	Description	Setting
Phases	# of Phases	3-Phase
kV	Voltage Level	User Defined
kW	Active Power	User Defined
kVAR	Reactive Power	User Defined
PF	Power Factor	User Defined
Model	Model Type	User Defined
Conn	Connection Type	Wye
Rneut	Neutral resistance: ohms	0
Vminpu	Min Voltage Level to operate at selected Model Type	User Defined
Vmaxpu	Max Voltage Level to operate at selected Model Type	User Defined
Xd	Per Unit synchronous reactance	1.0
Xdp	Per Unit transient reactance	.27
Xdpp	Per unit sub-transient reactance	.20

5.4 IEEE Test Case Data

The IEEE 13, IEEE 34 and IEEE 123 Distribution Test Cases were be used to conduct this research [2]. The Test Cases were modeled and simulated in DSS and interfaced with MATLAB to solve the power flow solutions with and without DG. The size and location of the DG were varied to obtain the respective power flow results for each DG configuration. The results will be used to help evaluate the overall performance of the multi-objective optimization DG placement and sizing algorithm.

Table 5.2 IEEE Test Cases Summary of System Data

Variable	Description	IEEE 13	IEEE 34	IEEE 123
Num of Nodes	Total # of Nodes	14	34	123
Num of 3-Phase Nodes	Total # of 3Phase Nodes (Eligible DG Locations)	9	26	66
Base kV	System Line-Line Voltage Level	4.16	24.9	4.16
kW Load	Total Active Power Load	3466	1769	3490
kVAR Load	Total Reactive Power	2102	1044	1920
Volt Deviation Index	Base Case Volt Deviation Index Calculation	.5201	1.36	3.02
kW Line Losses	Total Active Power Losses	101.29	167.68	870.90
kVAR Line Losses	Total Reactive Power Losses	284.57	-47.76	174.04
Freq	Base Frequency	60	60	60

5.4.1 IEEE 13-Node Base Case Data

Table 5.3 IEEE 13-Node Base Per-Unit Voltage Profile

Node	Phase 1	Phase 2	Phase 3
650	0.9998	0.9999	0.9999
671	0.9269	0.9906	0.9253
634	0.9486	0.9797	0.9514
645	0.9760	0.9561	0.0000
646	0.9744	0.9542	0.0000
692	0.9130	0.9945	0.9197
675	0.9073	0.9965	0.9180
611	0.9217	0.0000	0.0000
652	0.9199	0.0000	0.0000
670	0.9479	0.9860	0.9458
632	0.9583	0.9851	0.9579
680	0.9269	0.9906	0.9253
633	0.9550	0.9833	0.9557
684	0.9251	0.9235	0.0000

Table 5.4 IEEE 13-Node Base Case System Fault Current

Node	3-Phase Fault Current	Single-Phase- Ground Fault Current
671	5490	2993
634	5059	3038
645	6030	4211
646	4997	3545
692	4447	2585
675	4047	2412
611	2254	2254
652	2123	2123
670	8257	4495
632	11031	6005
680	4373	2383
633	7951	4531
684	3623	2521

5.4.2 IEEE 34-Node Base Case Data

Table 5.5 IEEE 34-Node Base Per-Unit Voltage Profile

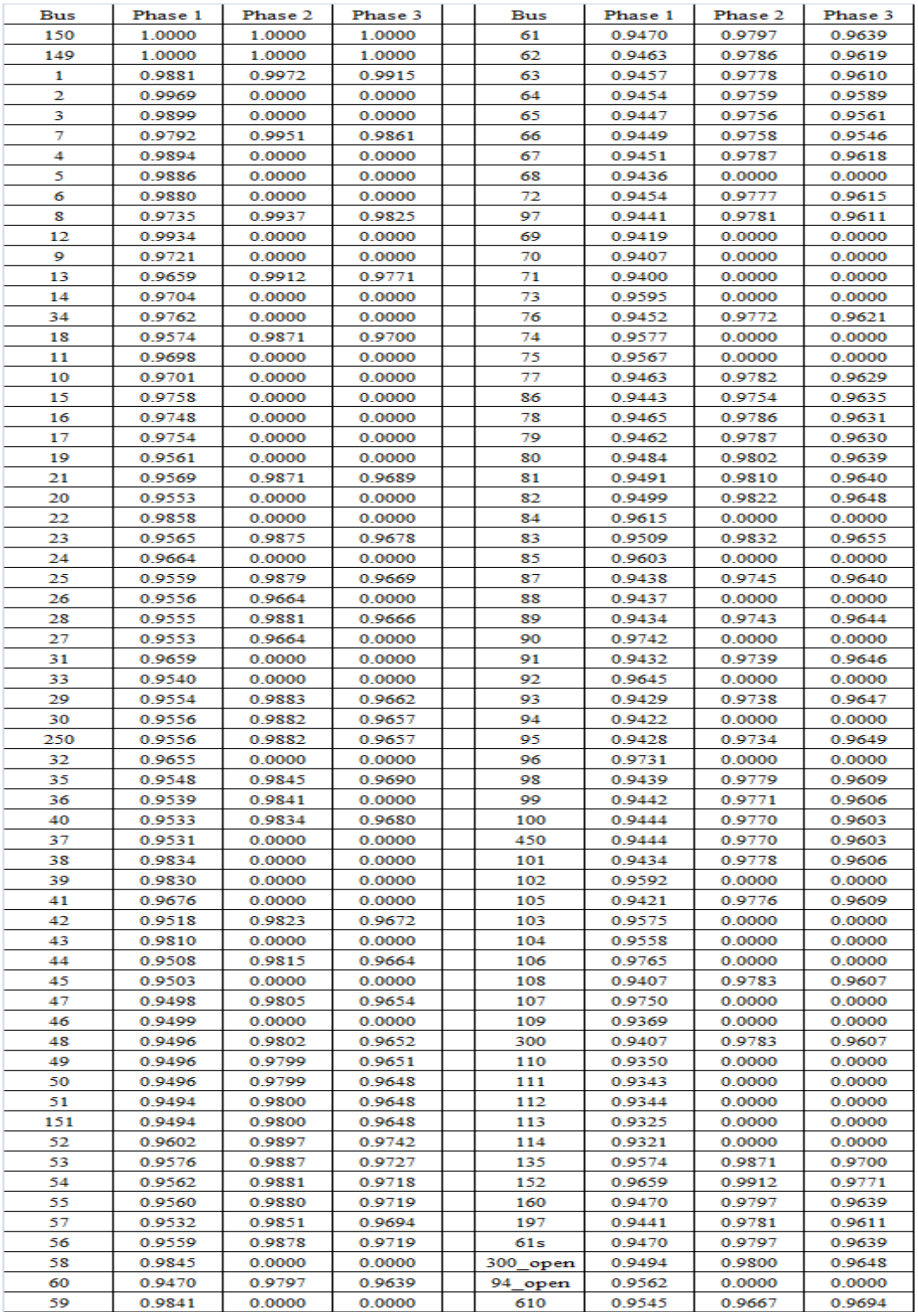
Node	Phase 1	Phase 2	Phase 3		Node	Phase 1	Phase 2	Phase 3
800	1.0500	1.0500	1.0500		832	0.9155	0.9443	0.9574
802	1.0479	1.0485	1.0488		858	0.9133	0.9419	0.9555
806	1.0466	1.0475	1.0480		834	0.9109	0.9392	0.9533
808	1.0205	1.0307	1.0340		860	0.9105	0.9388	0.9529
810	1.0305	0.0000	0.0000		842	0.9108	0.9391	0.9532
812	0.9902	1.0121	1.0173		836	0.9103	0.9384	0.9528
814	0.9660	0.9974	1.0040		840	0.9103	0.9384	0.9528
850	0.9660	0.9974	1.0040		862	0.9103	0.9384	0.9528
816	0.9656	0.9971	1.0038		844	0.9107	0.9388	0.9530
818	0.9648	0.0000	0.0000		846	0.9109	0.9387	0.9533
824	0.9579	0.9884	0.9969		848	0.9109	0.9387	0.9534
820	0.9427	0.0000	0.0000		852	0.9155	0.9443	0.9574
822	0.9399	0.0000	0.0000		888	0.9155	0.9443	0.9574
826	0.9882	0.0000	0.0000		856	0.9716	0.0000	0.0000
828	0.9573	0.9877	0.9963		864	0.9133	0.0000	0.0000
830	0.9420	0.9721	0.9822		838	0.9382	0.0000	0.0000
854	0.9416	0.9717	0.9818		890	0.9133	0.9422	0.9553

Table 5.6 IEEE 34-Node Base Case System Fault Current

Bus	3-Phase Fault Current	Single-Phase-Ground Fault Current		Bus	3-Phase Fault Current	Single-Phase-Ground Fault Current
802	22685	16250		858	287	206
806	13612	9742		834	276	199
808	1611	1148		860	272	196
810	911	911		842	275	198
812	795	565		836	267	193
814	567	402		840	265	192
850	567	402		862	266	192
816	565	400		844	272	197
818	382	382		846	266	192
824	499	356		848	265	191
820	217	217		852	297	213
822	193	193		888	297	213
826	341	341		856	223	223
828	494	352		864	196	196
830	400	287		838	187	187
854	398	286		890	281	202
832	297	213				

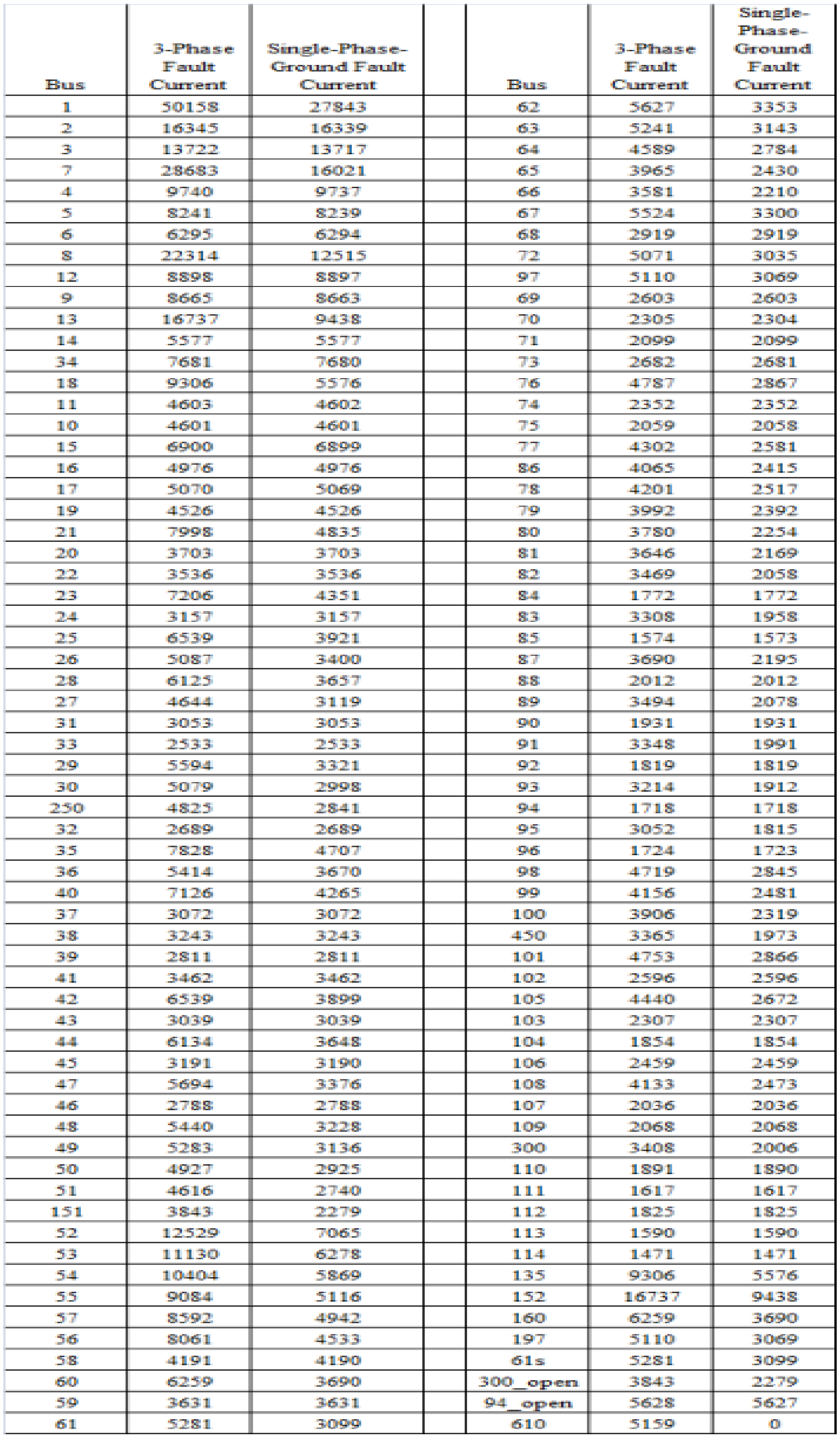
5.4.3 IEEE 123-Node Base Case Data

Table 5.7 IEEE 123-Node Base Per-Unit Voltage Profile



Bus	Phase 1	Phase 2	Phase 3		Bus	Phase 1	Phase 2	Phase 3
150	1.0000	1.0000	1.0000		61	0.9470	0.9797	0.9639
149	1.0000	1.0000	1.0000		62	0.9463	0.9786	0.9619
1	0.9881	0.9972	0.9915		63	0.9457	0.9778	0.9610
2	0.9969	0.0000	0.0000		64	0.9454	0.9759	0.9589
3	0.9899	0.0000	0.0000		65	0.9447	0.9756	0.9561
7	0.9792	0.9951	0.9861		66	0.9449	0.9758	0.9546
4	0.9894	0.0000	0.0000		67	0.9451	0.9787	0.9618
5	0.9886	0.0000	0.0000		68	0.9436	0.0000	0.0000
6	0.9880	0.0000	0.0000		72	0.9454	0.9777	0.9615
8	0.9735	0.9937	0.9825		97	0.9441	0.9781	0.9611
12	0.9934	0.0000	0.0000		69	0.9419	0.0000	0.0000
9	0.9721	0.0000	0.0000		70	0.9407	0.0000	0.0000
13	0.9659	0.9912	0.9771		71	0.9400	0.0000	0.0000
14	0.9704	0.0000	0.0000		73	0.9595	0.0000	0.0000
34	0.9762	0.0000	0.0000		76	0.9452	0.9772	0.9621
18	0.9574	0.9871	0.9700		74	0.9577	0.0000	0.0000
11	0.9698	0.0000	0.0000		75	0.9567	0.0000	0.0000
10	0.9701	0.0000	0.0000		77	0.9463	0.9782	0.9629
15	0.9758	0.0000	0.0000		86	0.9443	0.9754	0.9635
16	0.9748	0.0000	0.0000		78	0.9465	0.9786	0.9631
17	0.9754	0.0000	0.0000		79	0.9462	0.9787	0.9630
19	0.9561	0.0000	0.0000		80	0.9484	0.9802	0.9639
21	0.9569	0.9871	0.9689		81	0.9491	0.9810	0.9640
20	0.9553	0.0000	0.0000		82	0.9499	0.9822	0.9648
22	0.9858	0.0000	0.0000		84	0.9615	0.0000	0.0000
23	0.9565	0.9875	0.9678		83	0.9509	0.9832	0.9655
24	0.9664	0.0000	0.0000		85	0.9603	0.0000	0.0000
25	0.9559	0.9879	0.9669		87	0.9438	0.9745	0.9640
26	0.9556	0.9664	0.0000		88	0.9437	0.0000	0.0000
28	0.9555	0.9881	0.9666		89	0.9434	0.9743	0.9644
27	0.9553	0.9664	0.0000		90	0.9742	0.0000	0.0000
31	0.9659	0.0000	0.0000		91	0.9432	0.9739	0.9646
33	0.9540	0.0000	0.0000		92	0.9645	0.0000	0.0000
29	0.9554	0.9883	0.9662		93	0.9429	0.9738	0.9647
30	0.9556	0.9882	0.9657		94	0.9422	0.0000	0.0000
250	0.9556	0.9882	0.9657		95	0.9428	0.9734	0.9649
32	0.9655	0.0000	0.0000		96	0.9731	0.0000	0.0000
35	0.9548	0.9845	0.9690		98	0.9439	0.9779	0.9609
36	0.9539	0.9841	0.0000		99	0.9442	0.9771	0.9606
40	0.9533	0.9834	0.9680		100	0.9444	0.9770	0.9603
37	0.9531	0.0000	0.0000		450	0.9444	0.9770	0.9603
38	0.9834	0.0000	0.0000		101	0.9434	0.9778	0.9606
39	0.9830	0.0000	0.0000		102	0.9592	0.0000	0.0000
41	0.9676	0.0000	0.0000		105	0.9421	0.9776	0.9609
42	0.9518	0.9823	0.9672		103	0.9575	0.0000	0.0000
43	0.9810	0.0000	0.0000		104	0.9558	0.0000	0.0000
44	0.9508	0.9815	0.9664		106	0.9765	0.0000	0.0000
45	0.9503	0.0000	0.0000		108	0.9407	0.9783	0.9607
47	0.9498	0.9805	0.9654		107	0.9750	0.0000	0.0000
46	0.9499	0.0000	0.0000		109	0.9369	0.0000	0.0000
48	0.9496	0.9802	0.9652		300	0.9407	0.9783	0.9607
49	0.9496	0.9799	0.9651		110	0.9350	0.0000	0.0000
50	0.9496	0.9799	0.9648		111	0.9343	0.0000	0.0000
51	0.9494	0.9800	0.9648		112	0.9344	0.0000	0.0000
151	0.9494	0.9800	0.9648		113	0.9325	0.0000	0.0000
52	0.9602	0.9897	0.9742		114	0.9321	0.0000	0.0000
53	0.9576	0.9887	0.9727		135	0.9574	0.9871	0.9700
54	0.9562	0.9881	0.9718		152	0.9659	0.9912	0.9771
55	0.9560	0.9880	0.9719		160	0.9470	0.9797	0.9639
57	0.9532	0.9851	0.9694		197	0.9441	0.9781	0.9611
56	0.9559	0.9878	0.9719		61s	0.9470	0.9797	0.9639
58	0.9845	0.0000	0.0000		300_open	0.9494	0.9800	0.9648
60	0.9470	0.9797	0.9639		94_open	0.9562	0.0000	0.0000
59	0.9841	0.0000	0.0000		610	0.9545	0.9667	0.9694

Table 5.8 IEEE 123-Node Base Case System Fault Current



Bus	3-Phase Fault Current	Single-Phase-Ground Fault Current		Bus	3-Phase Fault Current	Single-Phase-Ground Fault Current
1	50158	27843		62	5627	3353
2	16345	16339		63	5241	3143
3	13722	13717		64	4589	2784
7	28683	16021		65	3965	2430
4	9740	9737		66	3581	2210
5	8241	8239		67	5524	3300
6	6295	6294		68	2919	2919
8	22314	12515		72	5071	3035
12	8898	8897		97	5110	3069
9	8665	8663		69	2603	2603
13	16737	9438		70	2305	2304
14	5577	5577		71	2099	2099
34	7681	7680		73	2682	2681
18	9306	5576		76	4787	2867
11	4603	4602		74	2352	2352
10	4601	4601		75	2059	2058
15	6900	6899		77	4302	2581
16	4976	4976		86	4065	2415
17	5070	5069		78	4201	2517
19	4526	4526		79	3992	2392
21	7998	4835		80	3780	2254
20	3703	3703		81	3646	2169
22	3536	3536		82	3469	2058
23	7206	4351		84	1772	1772
24	3157	3157		83	3308	1958
25	6539	3921		85	1574	1573
26	5087	3400		87	3690	2195
28	6125	3657		88	2012	2012
27	4644	3119		89	3494	2078
31	3053	3053		90	1931	1931
33	2533	2533		91	3348	1991
29	5594	3321		92	1819	1819
30	5079	2998		93	3214	1912
250	4825	2841		94	1718	1718
32	2689	2689		95	3052	1815
35	7828	4707		96	1724	1723
36	5414	3670		98	4719	2845
40	7126	4265		99	4156	2481
37	3072	3072		100	3906	2319
38	3243	3243		450	3365	1973
39	2811	2811		101	4753	2866
41	3462	3462		102	2596	2596
42	6539	3899		105	4440	2672
43	3039	3039		103	2307	2307
44	6134	3648		104	1854	1854
45	3191	3190		106	2459	2459
47	5694	3376		108	4133	2473
46	2788	2788		107	2036	2036
48	5440	3228		109	2068	2068
49	5283	3136		300	3408	2006
50	4927	2925		110	1891	1890
51	4616	2740		111	1617	1617
151	3843	2279		112	1825	1825
52	12529	7065		113	1590	1590
53	11130	6278		114	1471	1471
54	10404	5869		135	9306	5576
55	9084	5116		152	16737	9438
57	8592	4942		160	6259	3690
56	8061	4533		197	5110	3069
58	4191	4190		61s	5281	3099
60	6259	3690		300_open	3843	2279
59	3631	3631		94_open	5628	5627
61	5281	3099		610	5159	0

5.5 Optimal DG Sizing and Placement Solution

Many methods and techniques have been used to solve the DG optimal sizing and placement problem. These methods and techniques include the following: analytical, heuristic, numerical programming and artificial intelligence based. Prior to the wide spread use of artificial intelligence and numerical programming methods, engineers depended on analytical and intuitive methods based on rules of thumb and experience. While these techniques were used mainly as a guide, the solutions were not optimal solutions and the assumptions were typically impractical, depending on the size and complexity of the system.

As previously stated, the multi-objective index uses weight factors to give the system analyst the flexibility to customize the evaluation criteria. In solving the weighted multi-objective DG sizing and placement problem, the primary goal is to find the best solution for a particular set of evaluation criterion. In this research, six different weight factor combinations were used to evaluate the impact of DG on the system.

$$DGI_n^i = \left\{ w_1\, VDI_n^i \;+\; w_2\, FCI_n^i \;+\; w_3\, LI_n^i + w_4\, RI_n^i \right\} \tag{5.1}$$

Where, DGI_n^i = Distributed Generation Index for n^{th}DG location and i^{th}DG size

VDI_n^i = Voltage Deviation Index for n^{th}DG location and i^{th}DG size

FCI_n^i = Fault Current Index for n^{th}DG location and i^{th}DG size

LI_n^i = Power System Loss Index for n^{th}DG location and i^{th}DG size

RI_n^i = Reliability Index for n^{th}DG location and i^{th}DG size

w_i = Weight Factors used to select evaluation criteria

n = DG location

i = DG size

Where, $\sum_{i=1}^{4} w_i \;= 1 \;\forall\; w_i \;\in [0,1]$

Table 5.9 Simulation variables used to solve the Optimal DG Problem

Simulation #	w_1	w_2	w_3	w_4	DG Power factor	DG % Level
1	.35	.15	.35	.15	1.0	85
2	.25	.25	.25	.25	1.0	85
3	1.0	0.0	0.0	0.0	1.0	85
4	0.0	1.0	0.0	0.0	1.0	85
5	0.0	0.0	1.0	0.0	1.0	85
6	0.0	0.0	0.0	1.0	1.0	85

1) Simulation #1 represents a practical evaluation criterion for a typical distribution engineer. From a technical perspective, the typical engineer is primarily concerned with the voltage profile and the amount of system losses.
2) Simulation #2 represents a balanced approach to solving the optimal DG sizing and placement problem. Since all components are equally weighted, this simulation is expected to test the ability of the algorithm to converge without a dominant factor.
3) Simulation #3 is designed to evaluate the Voltage Deviation Index performance and to ensure that the algorithm is yielding the expected results.
4) Simulation #4 is designed to evaluate the Fault Current Index. The FCI is intended to be a supplemental index, preferably used in conjunction with the Voltage Deviation or Loss Index. Due to the nature of the Fault Current Index, the optimal DG algorithm will select the smallest size available and/or a location that provides results similar to the base case fault currents.
5) Simulation # 5 is designed to evaluate the Loss Index performance and to ensure that the algorithm is yielding the expected results.

6) Simulation # 6 is designed to evaluate the Reliability Index. This index is also intended to be a supplemental index, preferably used in conjunction with the Voltage Deviation or Loss Index. Due to the nature of the Reliability Index, the optimal DG size solution will be the largest available size.

To evaluate the performance of the particle swarm algorithm, an iteration based program was developed to solve the optimal DG sizing and placement problem for a single DG unit. This program was written in MATLAB and interfaced with DSS to solve the power flow solution. The results should coincide with the PSO solution for a single DG unit. Both programs use the same indices and multi-objective function to solve the problem. In order to solve the Optimal DG problem, specifically for particle swarm optimization, the nodes for each test case were re-numbered. Since PSO is a continuous based optimization algorithm, in order to transition from one location to another location, the nodes were re-numbered and the rounding method was used to make the nodes discrete. Each test case is solved separately.

The following is a list of simulation notes:

- Synchronous Generators were only installed at three-phase node locations.
- The synchronous generator power factor will be $.85 \leq pf_{DG} \leq 1.00$.
- Up to three generators will be placed on the system at a given time.
- Simulation results include the following information: per-phase voltage drop, system power losses, fault current levels, system load information and power flow results.

Although the generator and load models were converted to Const Z to help improve convergence and minimize the variations in the power flow solution, the generator experienced discrepancies in the input size of the DG and the actual size of the

DG installed on the system. During the simulation, the optimal DG sizing and placement algorithm compares the input DG size and the actual DG size, calculates the percent difference and reports the actual value of the DG installed on the system.

$$\%\,Difference = \frac{x_1 - x_2}{\frac{x_1 + x_2}{2}} * 100 \tag{5.2}$$

Where, x_1 = Actual DG size

x_2 = Input DG size

For example, if the input DG size is equaled 2500 kW, but the actual DG size placed on the system is equaled 2350 kW, then the percent difference is the following:

$$\%\,Difference = \frac{2350 - 2500}{\frac{2350 + 2500}{2}} * 100 = -6.2\% \tag{5.3}$$

The cause of the discrepancy is contributed to solving an ill conditioned system. The percent difference between the input size and the actual size typically ranged from 0% to ± 10.0 %. The margin of variation depends on the following parameters: system load conditions, size and location of DG, and system voltage conditions.

Due to the discrepancy in the DG size, an optional penalty factor was added to the multi-objective function to ensure that the optimal size remained within the user defined limit. The penalty factor may be enabled or disabled depending on system conditions. The following formulas and criteria were used to incorporate the penalty factor into the objective function:

$$DGPI_n^i = \frac{DGTotalkW_n}{TLoadkW_0} \tag{5.3}$$

$$DGI_n^i = \{w_1\, VDI_n^i + w_2\, FCI_n^i + w_3\, LI_n^i + w_4\, RI_n^i + pfactor * DGPI_n^i\} \tag{5.4}$$

$$\begin{Bmatrix} if\ DGPI_n^i > DGPL, & pfactor = \ .10 \leq \ pfactor \leq \ 1.00 \\ else, & pfactor = 0 \end{Bmatrix} \tag{5.5}$$

Where, DGI_n^i = Distributed Generation Index for n^{th} DG location and i^{th}DG size

VDI_n^i = Voltage Deviation Index for n^{th} DG location and i^{th}DG size

FCI_n^i = Fault Current Index for n^{th} DG location and i^{th}DG size

LI_n^i = Power System Loss Index for n^{th} DG location and i^{th}DG size

RI_n^i = Reliability Index for n^{th}DG location and i^{th}DG size

$DGPI_n^i$ = DG Penetration Index for n^{th}DG location and i^{th}DG size

$DGTotalkW_n$ = Total DG Active Power for n^{th}DG location

$TLoadkW$ = Total Connected kW Served

$DGPL$ = User Defined Maximum DG Penetration Level (i.e. 85%)

$pfactor$ = Penalty factor for excessive DG Penetration Level

w_i = Weight Factors used to select evaluation criteria

n = DG location

i = DG size

Where, $\sum_{i=1}^{4} w_i \ = 1 \ \forall \ w_i \ \in [0,1]$

5.5.1 Node Re-Numbering

Table 5.10 IEEE 13-Node Re-Numbering

Original Node	Re-Numbered Nodes
650	1
632	2
633	3
634	4
670	5
671	6
692	7
675	8
680	9

Table 5.11 IEEE 34-Node Re-Numbering

Original Node	Re-Numbered Nodes
800	1
802	2
806	3
808	4
812	5
814	6
850	7
816	8
824	9
828	10
830	11
854	12
852	13
832	14
888	15
858	16
834	17
842	18
890	19
844	20
860	21
836	22
862	23
846	24
840	25
848	26

Table 5.12 IEEE 123-Node Re-Numbering

Original Node	Re-Numbered Node		Original Node	Re-Numbered Node
150	1		97	34
149	2		197	35
1	3		72	36
7	4		30	37
8	5		76	38
13	6		50	39
152	7		101	40
52	8		98	41
53	9		250	42
54	10		64	43
18	11		51	44
135	12		105	45
55	13		77	46
57	14		78	47
21	15		99	48
35	16		108	49
56	17		76	50
23	18		79	51
40	19		65	52
25	20		100	53
42	21		80	54
60	22		151	55
160	23		87	56
28	24		81	57
44	25		66	58
62	26		89	59
47	27		82	60
67	28		300	61
29	29		91	62
48	30		450	63
61	31		83	64
63	32		93	65
49	33		95	66

5.5.2 Rule of Thumb Calculation

The Modified Rule of Thumb calculation is designed to give an approximation of the optimal size of the DG or DGs for a multi-objective index with similar attributes. The Rule of Thumb is just a snapshot approach to solving the optimal DG problem.

$$MRTSize_n = \left\{ w_1 \frac{2}{2N+.25} + w_2 \frac{1}{2N+3} + w_3 \frac{1}{N+.1} + w_4 \frac{1}{N+.1} \right\} * \frac{\sqrt{N}}{(n+.1)} \qquad (5.7)$$

Where, $MRTSize_n$ = Modified Rule of Thumb Size calculation for n^{th}number of DG

N = Total number of proposed DGs to install

w_i = Weight Factors used to select evaluation criteria

n = n^{th} number of DG

5.5.2.1 Modified Rule of Thumb Based IEEE 13-Node

Table 5.13 Rule of Thumb Based IEEE 13-Node One DG Optimal Sizing: N = 1

Simulation #	DG Power factor	kW Load	2/3 Rule of Thumb	Modified Rule of Thumb
1	1.0	3466	2311	2507
2	1.0	3466	2311	2290
3	1.0	3466	2311	2801
4	1.0	3466	2311	630
5	1.0	3466	2311	2864
6	1.0	3466	2311	2864

Table 5.14 Rule of Thumb Based IEEE 13-Node Two DG Optimal Sizing: N = 2

Simulation #	DG Power factor	kW Load	2/3 Rule of Thumb DG1	2/3 Rule of Thumb DG2	Modified Rule of Thumb DG1	Modified Rule of Thumb DG2
1	1.0	3466	1386	1386	1890	990
2	1.0	3466	1386	1386	1744	914
3	1.0	3466	1386	1386	2097	1098
4	1.0	3466	1386	1386	637	333
5	1.0	3466	1386	1386	2122	1111
6	1.0	3466	1386	1386	2122	1111

Table 5.15 Rule of Thumb Based IEEE 13-Node Three DG Optimal Sizing: N = 3

Simulation #	DG Power factor	kW Load	2/3 Rule of Thumb DG1	2/3 Rule of Thumb DG2	2/3 Rule of Thumb DG3	Modified Rule of Thumb DG1	Modified Rule of Thumb DG2	Modified Rule of Thumb DG3
1	1.0	3466	990	990	990	1582	829	562
2	1.0	3466	990	990	990	1468	769	521
3	1.0	3466	990	990	990	1746	915	620
4	1.0	3466	990	990	990	606	318	215
5	1.0	3466	990	990	990	1760	922	625
6	1.0	3466	990	990	990	1760	922	625

5.5.2.2 Modified Rule of Thumb Based IEEE 34-Node

Table 5.16 Rule of Thumb Based IEEE 34-Node One DG Optimal Sizing: N = 1

Simulation #	DG Power factor	kW Load	2/3 Rule of Thumb	Modified Rule of Thumb
1	1.0	1769	1179	1280
2	1.0	1769	1179	1169
3	1.0	1769	1179	1429
4	1.0	1769	1179	322
5	1.0	1769	1179	1462
6	1.0	1769	1179	1462

Table 5.17 Rule of Thumb Based IEEE 34-Node Two DG Optimal Sizing: N = 2

Simulation #	DG Power factor	kW Load	2/3 Rule of Thumb DG1	2/3 Rule of Thumb DG2	Modified Rule of Thumb DG1	Modified Rule of Thumb DG2
1	1.0	1769	707	707	965	505
2	1.0	1769	707	707	890	466
3	1.0	1769	707	707	1070	561
4	1.0	1769	707	707	325	170
5	1.0	1769	707	707	1083	567
6	1.0	1769	707	707	1083	567

Table 5.18 Rule of Thumb Based IEEE 34-Node Three DG Optimal Sizing: N = 3

Simulation #	DG Power factor	kW Load	2/3 Rule of Thumb DG1	2/3 Rule of Thumb DG2	2/3 Rule of Thumb DG3	Modified Rule of Thumb DG1	Modified Rule of Thumb DG2	Modified Rule of Thumb DG3
1	1.0	1769	505	505	505	808	423	287
2	1.0	1769	505	505	505	749	393	266
3	1.0	1769	505	505	505	891	467	316
4	1.0	1769	505	505	505	309	162	110
5	1.0	1769	505	505	505	899	471	319
6	1.0	1769	505	505	505	899	471	319

5.5.2.3 Modified Rule of Thumb Based IEEE 123-Node

Table 5.19 Rule of Thumb Based IEEE 123-Node One DG Optimal Sizing: N = 1

Simulation #	DG Power factor	kW Load	2/3 Rule of Thumb	Modified Rule of Thumb
1	1.0	3490	2327	2524
2	1.0	3490	2327	2306
3	1.0	3490	2327	2820
4	1.0	3490	2327	635
5	1.0	3490	2327	2884
6	1.0	3490	2327	2884

Table 5.20 Rule of Thumb Based IEEE 123-Node Two DG Optimal Sizing: N = 2

Simulation #	DG Power factor	kW Load	2/3 Rule of Thumb DG1	2/3 Rule of Thumb DG2	Modified Rule of Thumb DG1	Modified Rule of Thumb DG2
1	1.0	3490	1396	1396	1903	997
2	1.0	3490	1396	1396	1756	920
3	1.0	3490	1396	1396	2111	1106
4	1.0	3490	1396	1396	641	336
5	1.0	3490	1396	1396	2137	1119
6	1.0	3490	1396	1396	2137	1119

Table 5.21 Rule of Thumb Based IEEE 123-Node Three DG Optimal Sizing: N= 3

Simulation #	DG Power factor	kW Load	2/3 Rule of Thumb DG1	2/3 Rule of Thumb DG2	2/3 Rule of Thumb DG3	Modified Rule of Thumb DG1	Modified Rule of Thumb DG2	Modified Rule of Thumb DG3
1	1.0	3490	997	997	997	1593	835	565
2	1.0	3490	997	997	997	1479	775	525
3	1.0	3490	997	997	997	1759	921	624
4	1.0	3490	997	997	997	611	320	217
5	1.0	3490	997	997	997	1773	929	629
6	1.0	3490	997	997	997	1773	929	629

5.5.3 Iteration Based Approach

The optimal DG sizing and placement problem was solved for a single DG application using an iteration based approach. This approach places a generator at each three phase location and increases the size of the DG based on a user defined incremental value. This approach can be computational intensive depending on the size of the power system and the number of possible DG locations.

5.5.3.1 Iteration Based Approach Algorithm

The iteration based approach used the following steps to solve the optimal DG sizing and placement:

Step 1: Initialize MATLAB & DSS

The algorithm is written in MATLAB and interfaced with DSS to solve the power flow solutions. The following commands are executed in MATLAB to initialize DSS:

1) Obj = actxserver('OpenDSSEngine.DSS'): Instantiate the DSS Object:
2) Start = Obj.Start(0):Start DSS (Only execute once per MATLAB session)
3) Text = Obj.Text: Define the text command interface

Step 2: Define System Parameters

The following user defined parameters must be established to solve the optimal DG problem:

1) Simulation Parameters
    a. Weight Factors for multi-objective function
2) DG Parameters
    a. DG Power Factor
    b. DG Penetration Level
    c. DG Minimum kW Size
    d. DG Incremental step size

Step 3: Import IEEE Test Case Circuit Data

The imported files are written in DSS format and saved in a user defined directory. A DSS text command to import and compile the circuit data for IEEE Test Case is transmitted from MATLAB to DSS.

Step 4: Solve Base Case Power Flow in DSS

DSS solves the power flow solution for the given test system to calculate system parameters without a generator.

Step 5: Export & Store Power Flow Results in MATLAB

The following data is exported and stored in MATLAB and used to solve the optimal DG size and location:

1) Per Unit Node Voltages
2) Active & Reactive Power Losses for each line section and power elements
3) Fault Current Levels
4) System Load Data

Step 6: Define and Install DG(s) on the System

A new generator is defined and placed onto the system. The following is a list of user defined parameters:

1) Temporary Location (i.e. Node 650)
2) Voltage Rating (i.e. 4.16 kV)
3) Size (i.e. 100 kW)
4) Connection type (i.e. Wye)
5) Model Type (i.e. Const Z)

Step 7: Solve Power Flow Results in DSS for each DG configuration

The DG location is selected and the size is increased based on the user defined step size. DSS solves the power flow for that particular size and location.

Step 8: Export Results to MATLAB & Calculate the Multi-Objective Index for each DG Configuration Using Equation 5.1

Step 9: Export & Display the Optimal DG Size & Location Results

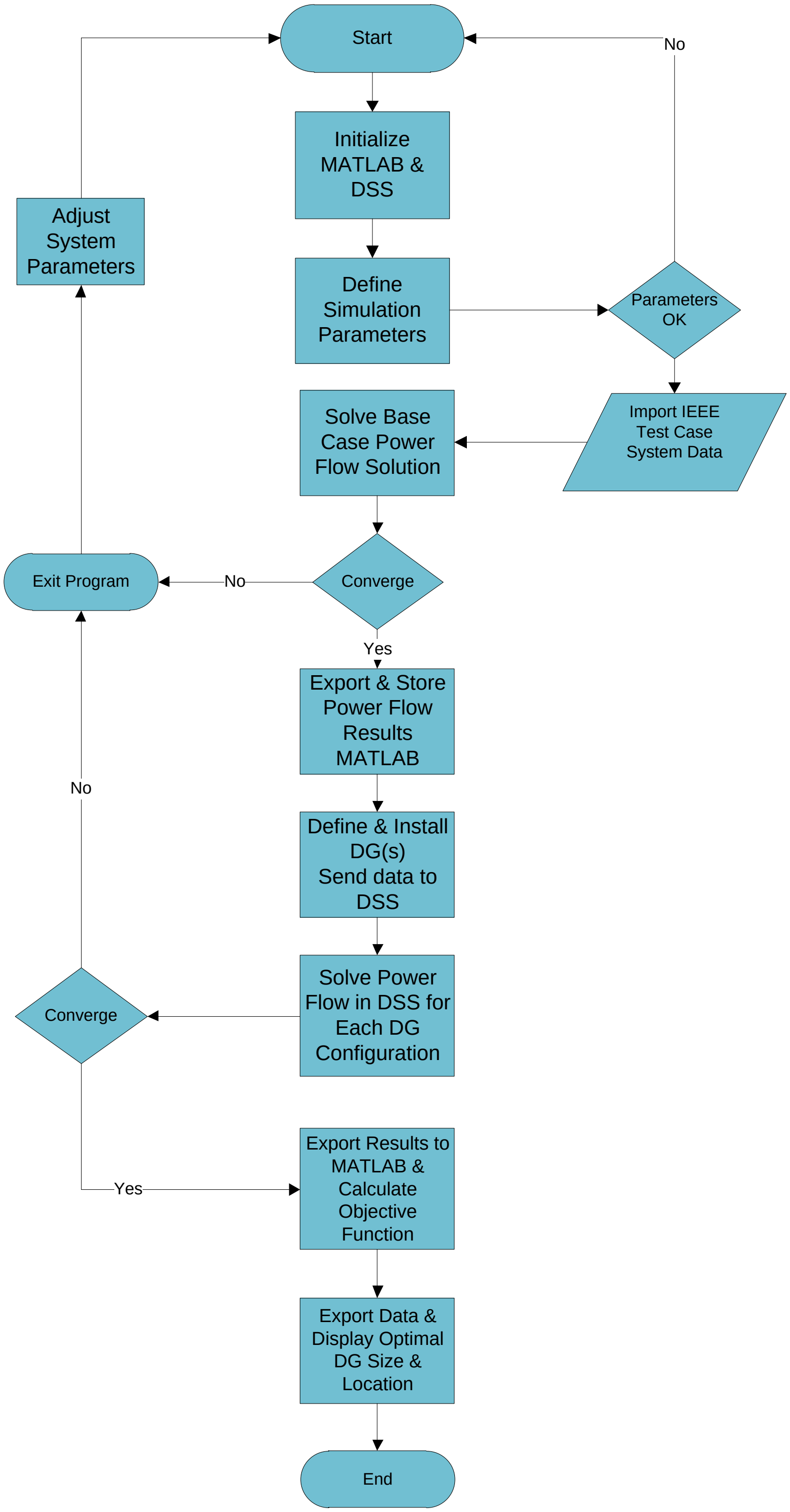


Figure 5.2 Iteration Based Optimal DG Sizing & Placement Flow Chart

Table 5.22 Iteration Based Approach Simulation Parameters

Variable	Description	IEEE 13	IEEE 34	IEEE 123
kW Load	Total Active Power Load	3466	1769	3490
kW Line Losses	Total Active Power Losses	101.29	167.68	870.90
kVAR Line Losses	Total Reactive Power Losses	284.57	47.76	174.04
Number of DG	# of DG to install on system (User Defined)	1	1	1
DG Power Factor	Power Factor of DG(s)	1.0	1.0	1.0
DG Penetration Level	Max DG kW Size as a percentage of kW Load	85%	85%	85%
DG Minimum Size	Minimum size of DG	0	0	0
DG Step Size	Step Size Increment (kW)	25	25	25
DG Max Size	Maximum Size of DG to install	2946	1504	2967
Weight Factors	Weight Factors for Multi-Objective Function (User Defined)	Various	Various	Various
pFactor	Penalty Factor for DG Penetration Levels outside of specified limits (User defined) pfactor = .50	0.0	0.0	0.0

5.5.3.2 Iteration Based IEEE 13-Node Single DG Sizing & Placement

Table 5.23 Iteration Based IEEE 13-Node Optimal DG Sizing & Placement: Step Size = 25kW

Simulation #	Max DG Size	VDI	FCI	LI	RI	DGI	Iteration Optimal Location	Iteration Optimal Size	% Diff in Size	Total Iteration Time (secs)	kWLoss	kVarLoss
1	2946	.3485	.2484	.2839	.1950	.2878	671	2790	-5.6%	139.9	39.8	-75.9
2	2946	.3485	.2484	.2839	.1950	.2690	671	2790	-5.6%	134.4	39.8	-75.9
3	2946	.3450	.2498	.3537	.1783	.3450	692	2848	-3.5%	136.2	56.1	-90.9
4	2946	.5201	.0000	1.000	.9928	.0000	650	25	0.0%	133.6	101.3	-284.6
5	2946	.3485	.2484	.2839	.1950	.2839	671	2790	-5.6%	134.0	39.8	-75.9
6	2946	.5196	.0001	1.001	.1492	.1492	650	2949	-0.0%	135.7	101.3	-284.6

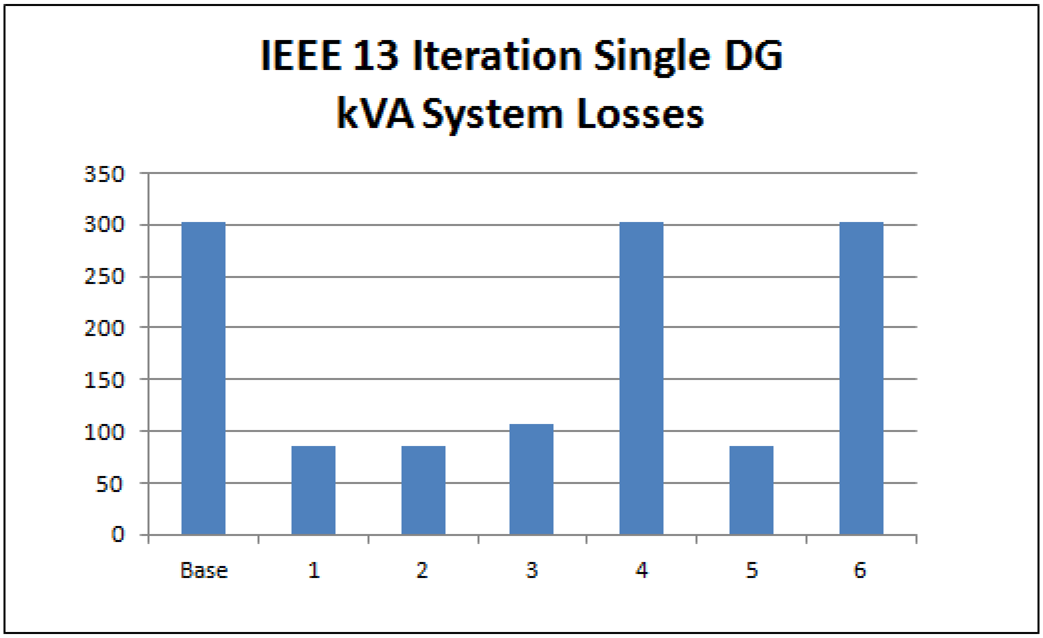


Figure 5.3 IEEE 13 Iteration Based kVA Losses

5.5.3.3 Iteration Based IEEE 34-Node Single DG Sizing & Placement

Table 5.24 Iteration Based IEEE 34-Node Optimal DG Sizing & Placement: Step Size = 25 kW

Simulation #	Max DG Size	VDI	FCI	LI	RI	DGI	Iteration Optimal Location	Iteration Optimal Size	% Diff in Size	Total Iteration Time (secs)	kWLoss	kVarLoss
1	1504	.6157	.1979	.8126	.5235	.6081	840	843	-0.8%	331.3	47.5	-133.4
2	1504	.7472	.1891	.8543	.1651	.4889	828	1477	7.2%	677.4	76.7	-127.1
3	1504	.6156	.1979	.8128	.5235	.6156	836	843	-0.8%	1015	47.2	-133.6
4	1504	1.361	.0000	1.000	.9842	.0000	800	28	11.3%	1356	167.7	-47.8
5	1504	.7728	.1376	.7756	.7060	.7756	844	520	-5.6%	1688.8	80.3	-108.7
6	1504	.7965	.2247	.8645	.1504	.1504	830	1503	7.1%	2033.8	55.9	-139.9

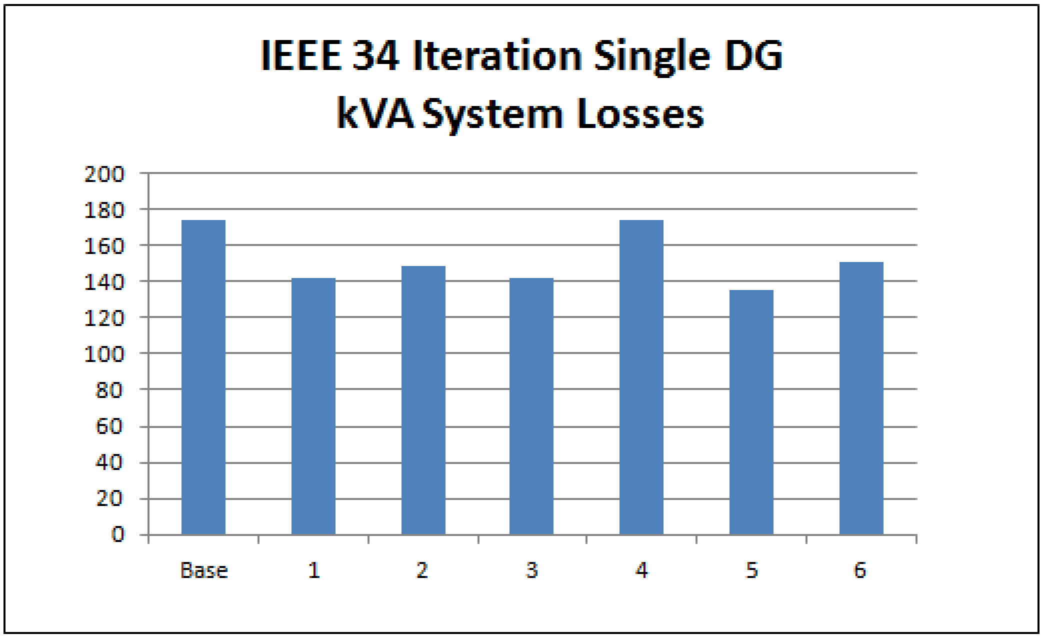


Figure 5.4 IEEE 34 Iteration Based kVA Losses

5.5.3.4 Iteration Based IEEE 123-Node Single DG Sizing & Placement

Table 5.25 Iteration Based IEEE 123-Node Optimal DG Sizing & Placement: Step Size = 25kW

Simulation #	Max DG Size	VDI	FCI	LI	RI	DGI	Iteration Optimal Location	Iteration Optimal Size	% Diff in Size	Total Iteration Time (secs)	kWLoss	kVarLoss
1	2967	1.358	.1765	.3833	.1562	.6596	67	2945	-1.0%	5702	35.4	-65.6
2	2967	1.358	.1765	.3833	.1562	.5187	67	2945	-1.0%	11440	35.4	-65.6
3	2967	1.350	.1801	.4246	.1521	1.350	72	2959	-0.5%	17144	38.9	-72.8
4	2967	3.020	.0000	1.000	.9928	.0000	150	25	0.0%	22953	87.1	-174.0
5	2967	1.570	.1501	.3270	.3499	.3270	67	2269	-2.4%	28859	30.4	-55.9
6	2967	1.838	.1008	.9558	.1501	.1501	49	2966	-0.3%	34721	83.9	-165.9

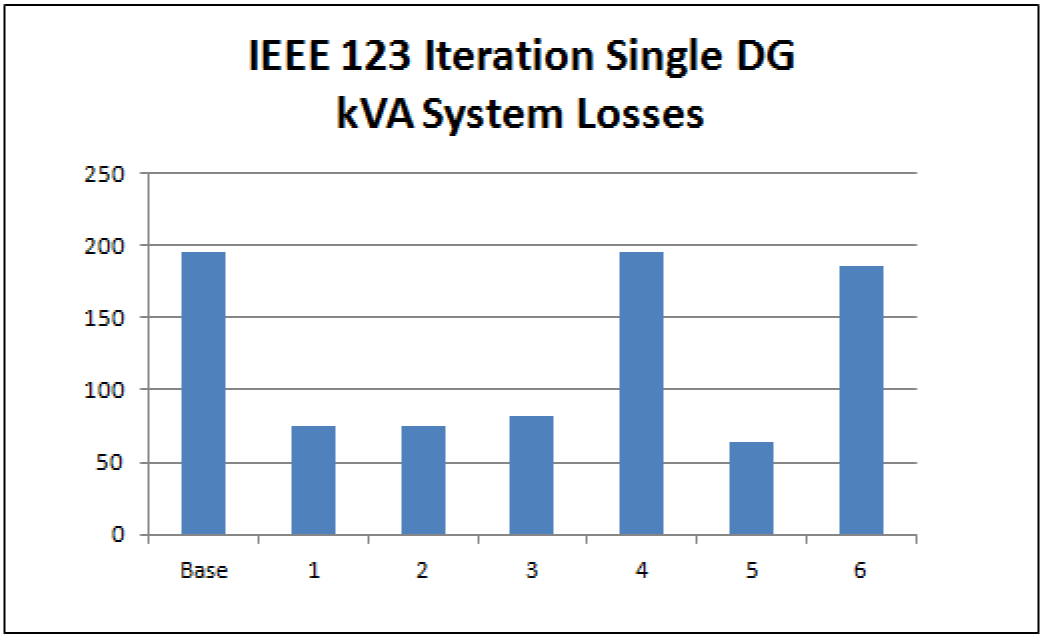


Figure 5.5 IEEE 123 Iteration Based kVA Losses

5.5.4 Particle Swarm Based Approach

As stated in Chapter 2, Particle Swarm Optimization is a multipoint, population based search algorithm that was introduced by James Kennedy and Russell Eberhart in 1995 [3]. PSO has been modified over the years to help improve the convergence and accuracy rate. PSO is one of several evolutionary algorithms. Evolutionary algorithms are population based optimization techniques. PSO is traditionally used to solve continuous optimization problems, but can be adapted to solve discrete optimization problems. Of the many types of evolutionary algorithms; particle swarm is preferred primarily because of its computational efficiency, simplicity and high convergence rate.

5.5.4.1 PSO Based Approach Algorithm

Step 1: Initialize MATLAB & DSS

The algorithm is written in MATLAB and interfaced with DSS to solve the power flow solutions. The following commands are executed in MATLAB to initialize DSS:

1) Obj = actxserver('OpenDSSEngine.DSS'): Instantiate the DSS Object:
2) Start = Obj.Start(0):Start DSS (Only execute once per MATLAB session)
3) Text = Obj.Text: Define the text command interface

Step 2: Define System/Simulation Parameters

The following user defined parameters must be established to solve the optimal DG problem:

1) Simulation Parameters
    a. Max Iterations
    b. Termination Criteria
    c. Weight Factors for multi-objective function
2) DG Parameters
    a. Number of DG
    b. DG Power Factor
    c. DG Penetration Level
    d. DG Minimum kW Size
3) PSO Parameters
    a. Swarm Size
    b. Cognitive Coefficient
    c. Social Coefficient
    d. Inertia Weight
    e. Velocity Constriction Factor

f. Initial Fitness Value

Step 3: Import IEEE Test Case Circuit Data

The imported files are written in DSS format and saved in a user defined directory. A DSS text command to import and compile the circuit data for IEEE Test Case is transmitted from MATLAB to DSS.

Step 4: Solve Base Case Power Flow in DSS

DSS solves the power flow solution for the given test system to calculate system parameters without a generator.

Step 5: Export & Store Power Flow Results in MATLAB

The following data is exported and stored in MATLAB and used to solve the optimal DG size and location:

1) Per Unit Node Voltages
2) Active & Reactive Power Losses for each line section and power elements
3) Fault Current Levels
4) System Load Data

Step 6: Define and Install DG(s) on the System

A new generator is defined and placed onto the system. The following is a list of user defined parameters:

1) Temporary Location (i.e. Node 650)
2) Voltage Rating (i.e. 4.16 kV)
3) Size (i.e. 100 kW)
4) Connection type (i.e. Wye)
5) Model Type (i.e. Const Z)

Step 7: Optional Calculation: Pre-screen with Rule of Thumb/User Defined

1) The Original or Modified Rule of Thumb Size is calculated or a user defined DG size is given
2) The DG is placed at an eligible location.
3) DSS solves the power flow for that particular size and location.
4) Power flow results are exported to MATLAB
5) The multi-objective index is calculated for each DG configuration using equation 5.1
6) Store the best results (i.e. DG configuration with the smallest objective index)

Step 8: Initialize Particle Swarm

1) Randomly select a feasible size and actual location for each particle (i.e. If the number of DG = 2, then each particle will have a size and location associated with each DG. Each particle will have four values.
2) For the 1st iteration, the velocity vectors are equaled to zero.
3) If Pre-screen selected, then over-ride the 1st particle with the best results from pre-screen calculations.

Step 9: Verify Particle in feasible region

Step 10: Solve Power Flow Results in DSS for each DG configuration

Step 11: Export Results to MATLAB & Calculate the Multi-Objective Index for each particle (DG Configuration) Using Equation 5.1

Step 12: Measure fitness of each particle and store the individual best ($pbest_i$) & store the overall best (gbest)

Step 13: Check Termination Criteria

1) Max # of Iterations
2) User Defined # of iterations the objective value remained the same or did not change by a specified value (i.e. Theta = .0001).
3) Target Objective met (i.e. Objective = 0)

Step 14: If Termination criteria met, Go to Step 17, else go to step 15

Step 15: Calculate new velocity according to equation 2.1 and equation 2.3 for velocity clamping and updating particles according to equations 2.2.

Step 16: Repeat steps 9-13

Step 17: Export & Display the Optimal DG Size & Location Results

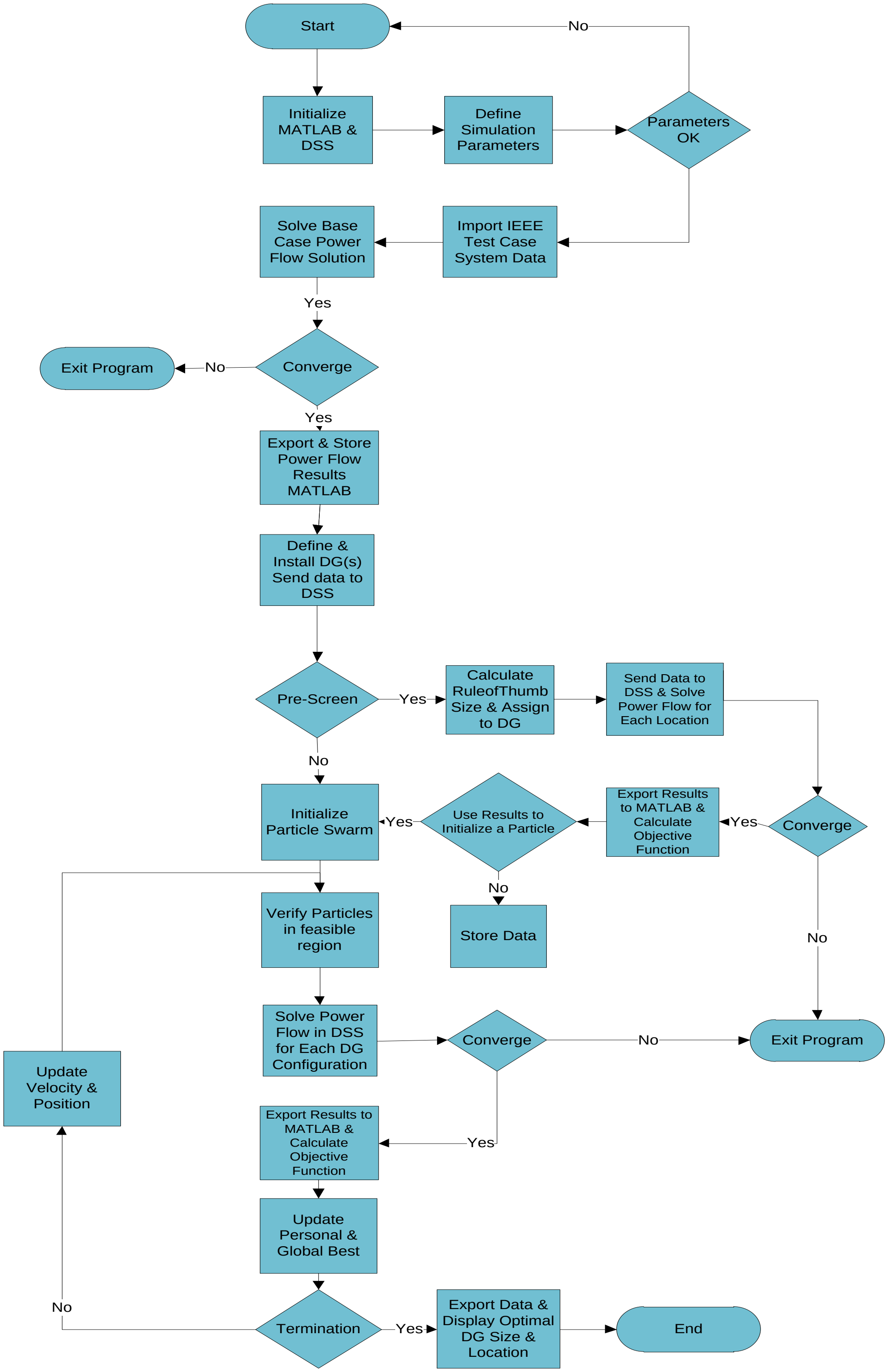


Figure 5.6 PSO Based Optimal DG Sizing & Placement Flow Chart

Table 5.26 PSO Based Approach Simulation Parameters

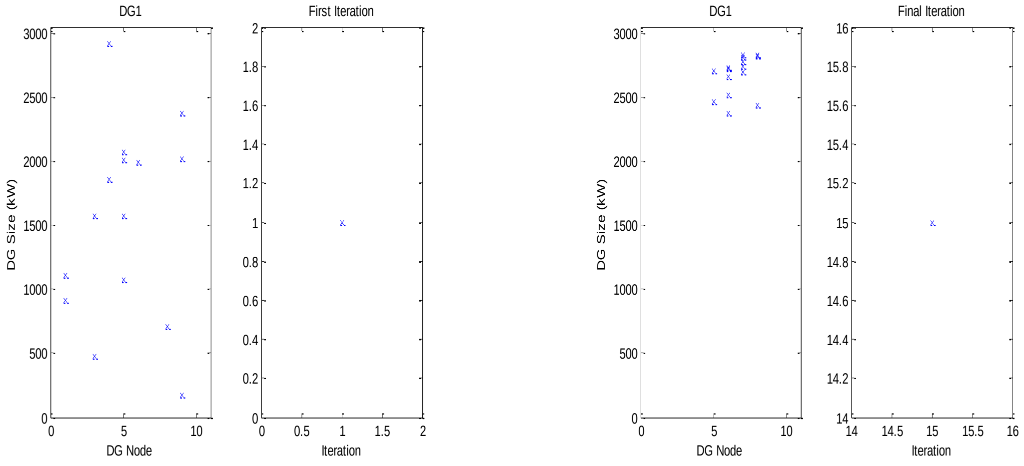
Variable	Description	IEEE 13	IEEE 34	IEEE 123
kW Load	Total Active Power Load	3466	1769	3490
kW Line Losses	Total Active Power Losses	101.29	167.68	870.90
kVar Line Losses	Total Reactive Power Losses	-284.57	-47.76	-174.04
# of Iterations	Max # of iterations to run simulation	100	100	100
Termination Criteria	# of Iterations the objective function remains the same or does not change more than a user defined value (i.e. Theta = .0001)	5	5	5
Theta	Termination criteria: Compares difference in objective function	.0001	.0001	.0001
Weight Factors	Weight Factors for Multi-Objective Function (User Defined)	Various	Various	Various
Number of DG	# of DGs to install on system (User Defined)	Various	Various	Various
DG Power Factor	Power Factor of DG(s)	1.0	1.0	1.0
DG Penetration Level	Max DG kW Size as a percentage of kW Load	85%	85%	85%
DG Minimum Size	Minimum size of DG	0	0	0
DG Max Size	Maximum Size of DG to install	2946	1504	2967
pFactor	Penalty Factor for DG Penetration Levels outside of specified limits (User defined) pfactor = .50	0.5	0.50	0.50
Swarm Size	# of Particles used to search solution space	15	15	15
C_1	Cognitive Coefficient	1.5	1.5	1.5
C_2	Social Coefficient	1.2	1.2	1.2
w_1	Inertia Weight	.85	.85	.85
Initial Fitness	Initial Value to compare objective function results	10000	10000	10000
k_{DGLoc}	Constriction Factor for Location: Velocity Clamping	.35	.35	.35
k_{DGSize}	Constriction Factor for Size: Velocity Clamping	.25	.25	.25

5.5.4.2 PSO Based IEEE 13-Node Results

5.5.4.2.1 IEEE 13-Node One DG Sizing & Placement

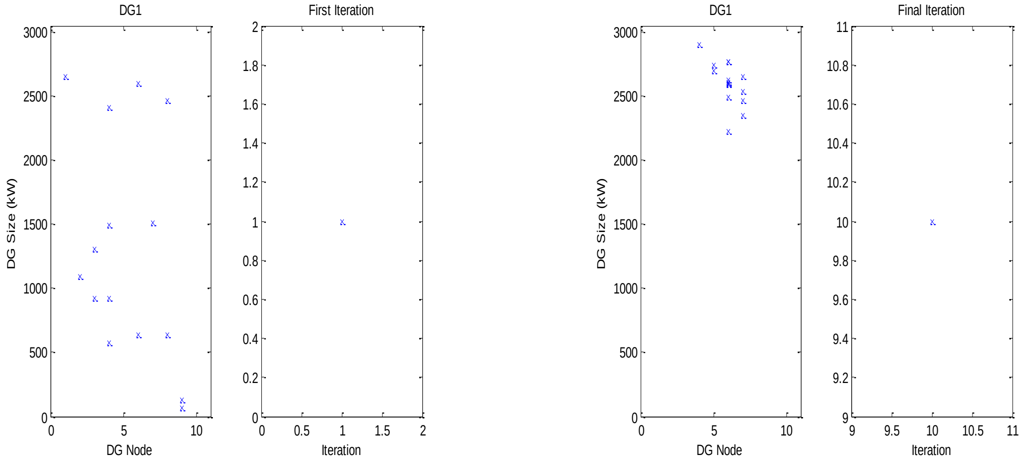
Table 5.27 PSO Based IEEE 13-Node Optimal One DG Sizing & Placement

Simulation #	1	2	3	4	5	6
VDI	.3492	.3488	.3453	.5201	.3491	.3477
FCI	.2477	.2481	.2496	.0000	.2478	.2448
LI	.2840	.2839	.3532	1.000	.2840	.3962
RI	.1994	.1968	.1797	.9729	.1988	.1815
DGI	.2887	.2694	.3453	.0000	.2840	.1815
Theta	.0001	.0001	.0001	.0001	.0001	.0001
PSO DG1 Location	671	671	692	650	671	675
PSO DG1 Size	2775	2784	2843	94	2777	2837
% Diff Size	-5.6%	-5.6%	-3.5%	0.0%	-5.6%	-2.4%
Total DG Size	2775	2784	2843	28	2777	2837
Total Max Limit DG Size	2946	2946	2946	2946	2946	2946
Total Time to find Optimal Solution (secs)	20.7	19.0	30.2	10.2	15.8	15.5
Total Simulation Time (secs)	31.2	21.1	41.1	13.4	26.9	26.5
kWLoss	39.8	39.8	55.9	101.3	39.8	65.9
kVarLoss	-75.9	-75.9	-90.8	-284.6	-75.9	-99.8



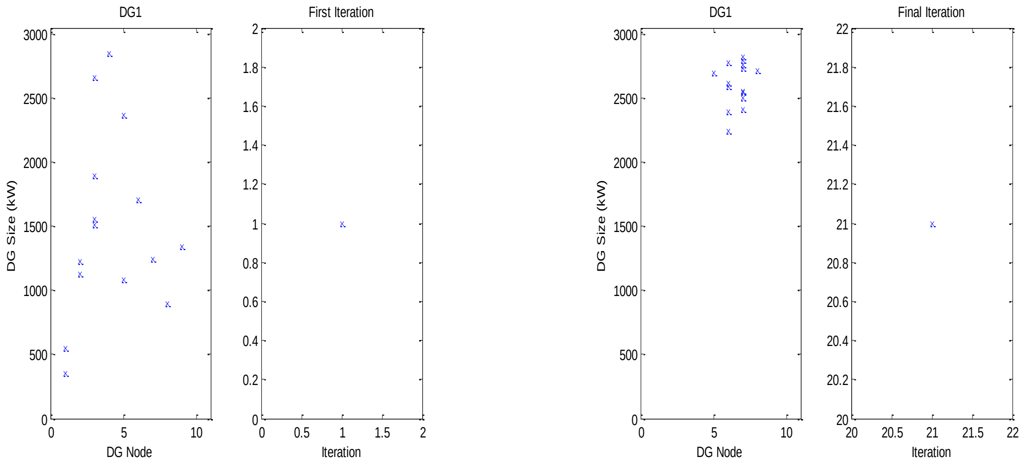
(a) (b)

Figure 5.7 Simulation #1 IEEE 13 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 15



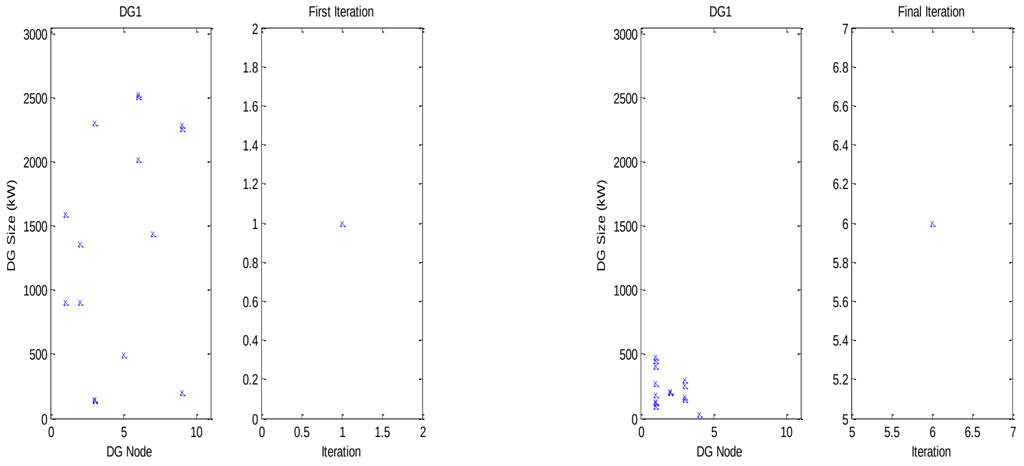
(a) (b)

Figure 5.8 Simulation #2 IEEE 13 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 10



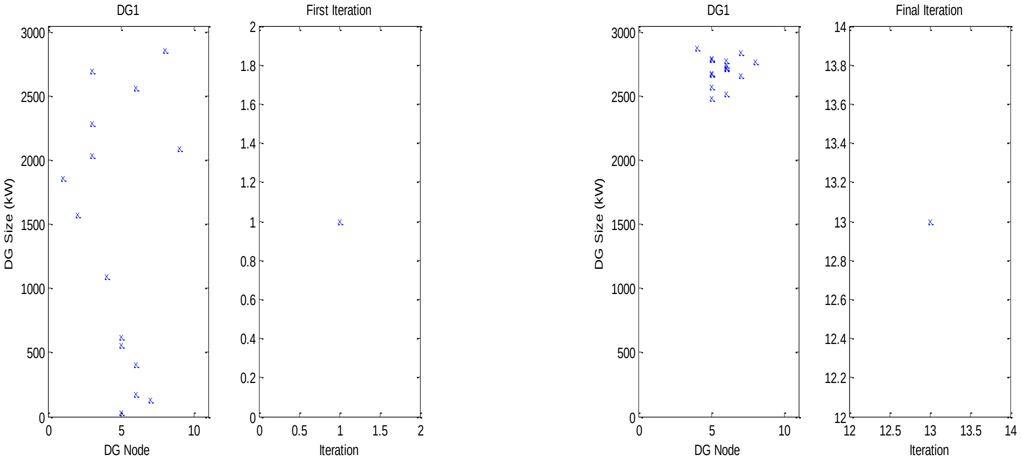
(a) (b)

Figure 5.9 Simulation #3 IEEE 13 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 21



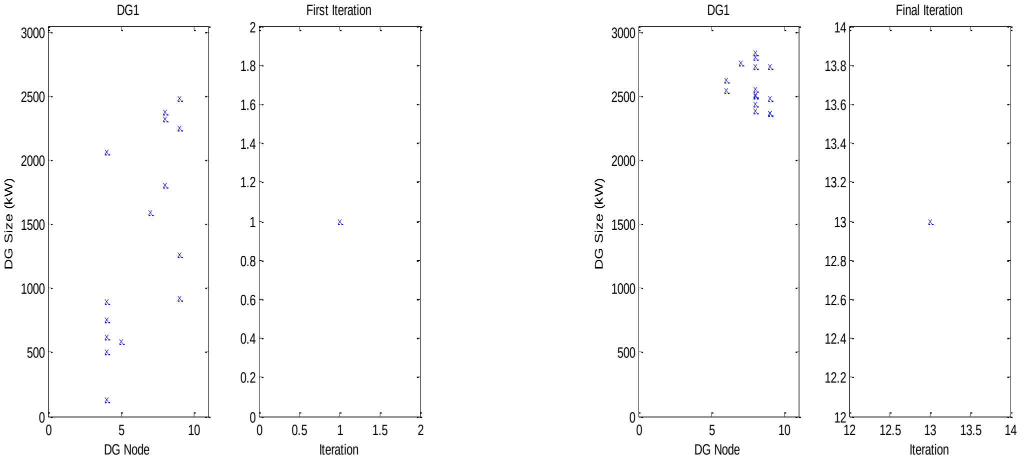
(a) (b)

Figure 5.10 Simulation #4 IEEE 13 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 6



(a) (b)

Figure 5.11 Simulation #5 IEEE 13 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 13



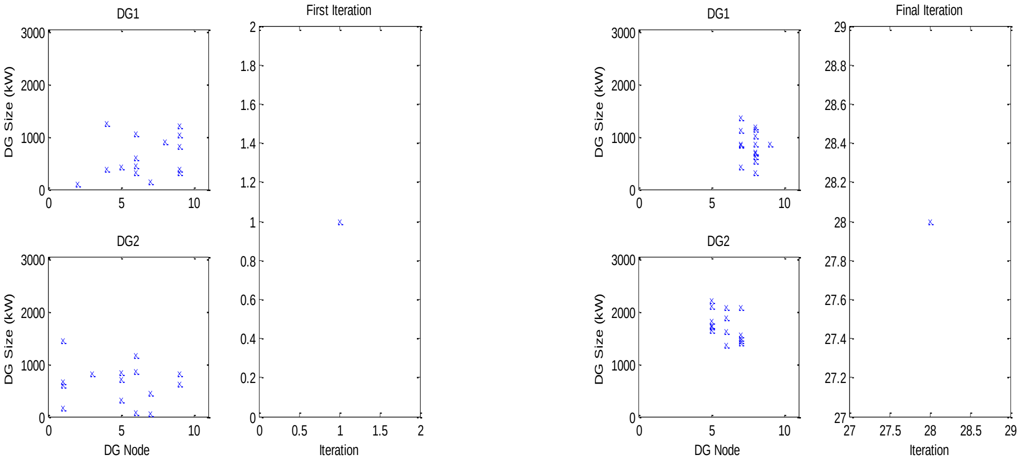
(a) (b)

Figure 5.12 Simulation #6 IEEE 13 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 13

5.5.4.2.2 IEEE 13-Node Two DG Sizing & Placement

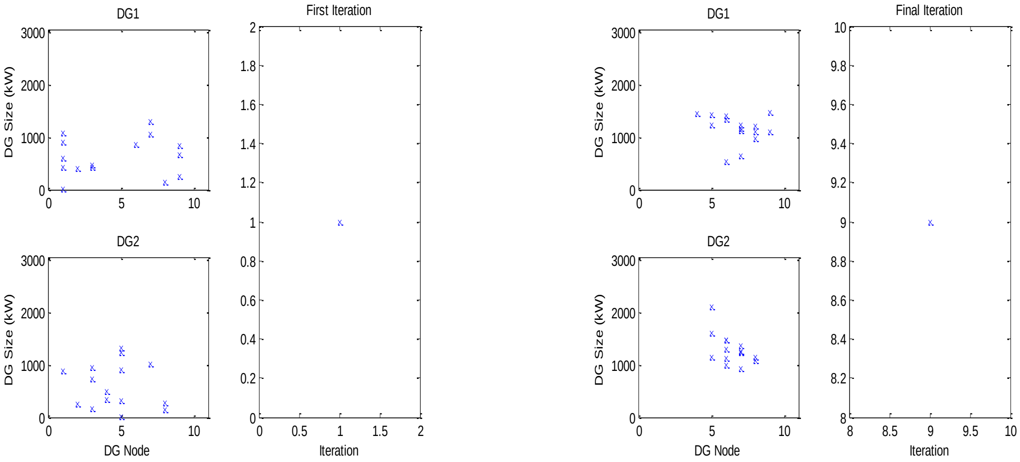
Table 5.28 PSO Based IEEE 13-Node Optimal Two DG Sizing & Placement

Simulation #	1	2	3	4	5	6
VDI	.3480	.3479	.3480	.5199	.3485	.3991
FCI	.2494	.2495	.2498	.0002	.2489	.1455
LI	.2613	.2676	.3139	.9990	.2628	.5367
RI	.2011	.2034	.2043	.9991	.2054	.1500
DGI	.2808	.2671	.3480	.0002	.2628	.1500
Theta	.0001	.0001	.0001	.0001	.0001	.0001
PSO DG1 Location	675	692	680	675	675	632
PSO DG1 Size	628	1171	1260	2	1122	2458
% Diff Size	-6.0%	-5.4%	-5.2%	0.0%	-5.1%	-4.1%
PSO DG2 Location	671	671	692	650	671	632
PSO DG2 Size	2141	1590	1498	1	1632	488
% Diff DG2 Size	-5.60%	-5.6%	-5.1%	0.0%	-5.6%	-4.0%
Total DG Size	2769	2761	2758	3	2754	2946
Total Max Limit DG Size	2946	2946	2946	2946	2946	2946
Total Time to find Optimal Solution (secs)	47.3	10.3	13.6	22.8	36.7	35.5
Total Simulation Time (secs)	59.9	21.8	24.9	33.5	39.8	48.4
kWLoss	34.1	35.6	40.7	101.1	33.7	60.6
kVarLoss	-71.2	-72.6	-85.6	-284.3	-70.9	-150.3



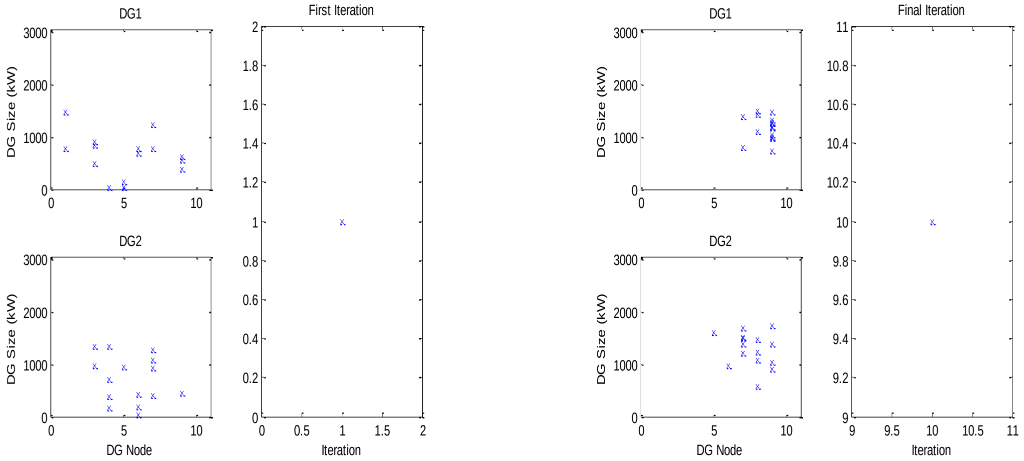
(a) (b)

Figure 5.13 Simulation #1 IEEE 13 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 28



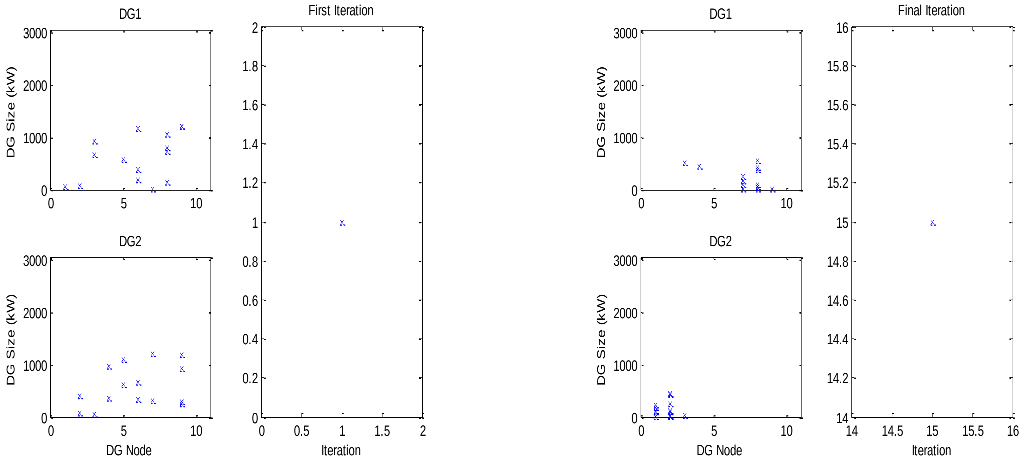
(a) (b)

Figure 5.14 Simulation #2 IEEE 13 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 9



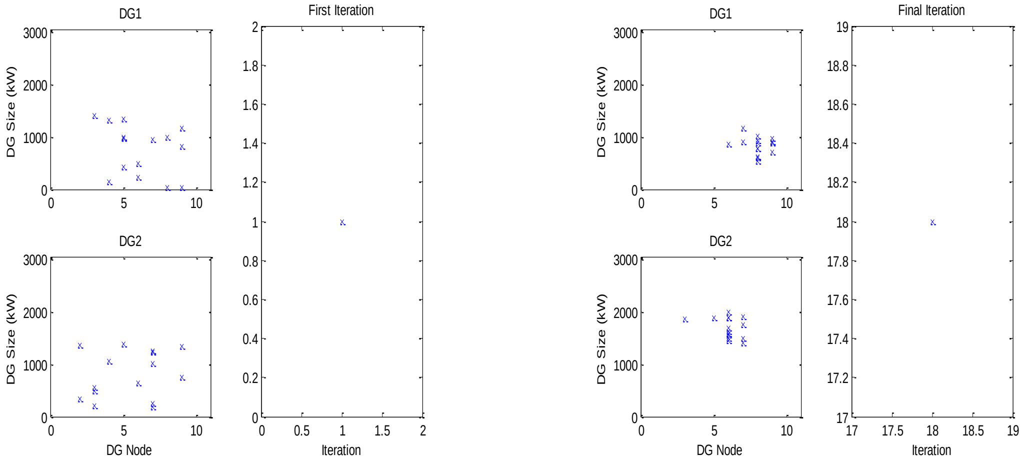
(a) (b)

Figure 5.15 Simulation #3 IEEE 13 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 10



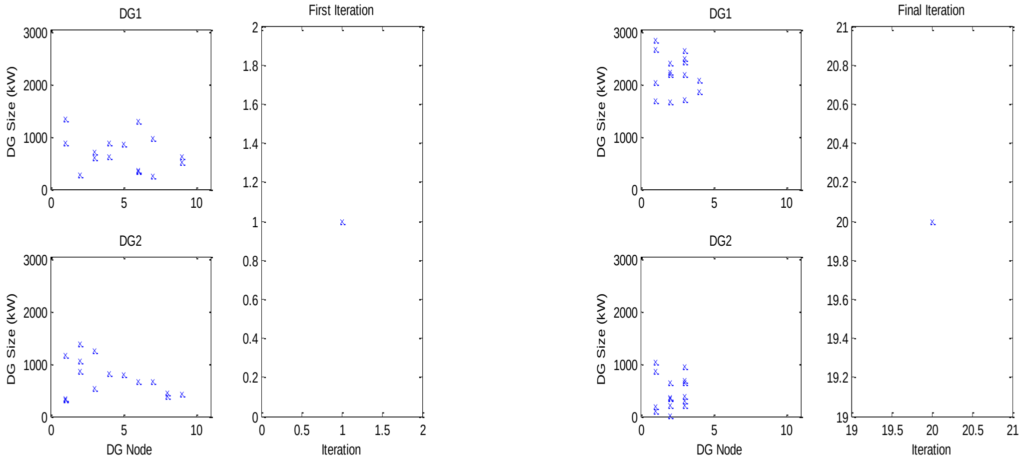
(a) (b)

Figure 5.16 Simulation #4 IEEE 13 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 15



(a) (b)

Figure 5.17 Simulation #5 IEEE 13 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 18



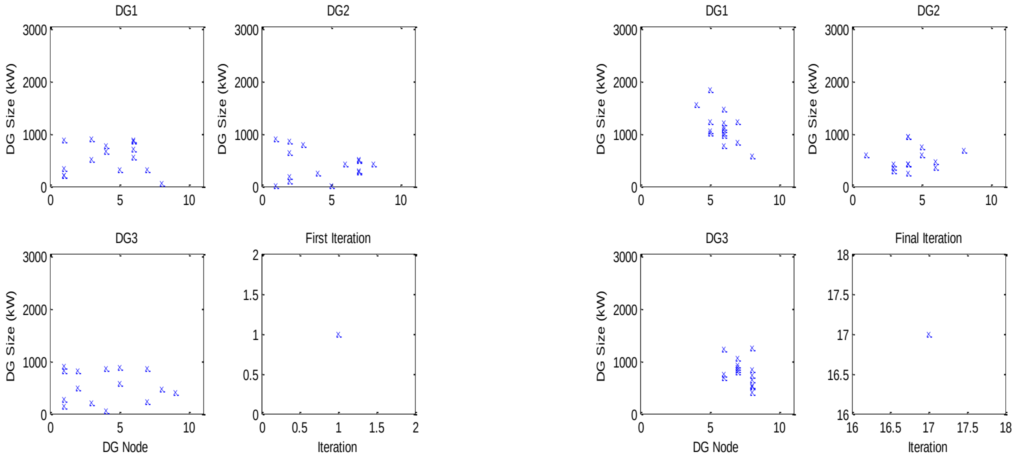
(a) (b)

Figure 5.18 Simulation #6 IEEE 13 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 20

5.5.4.2.3 IEEE 13-Node Three DG Sizing & Placement

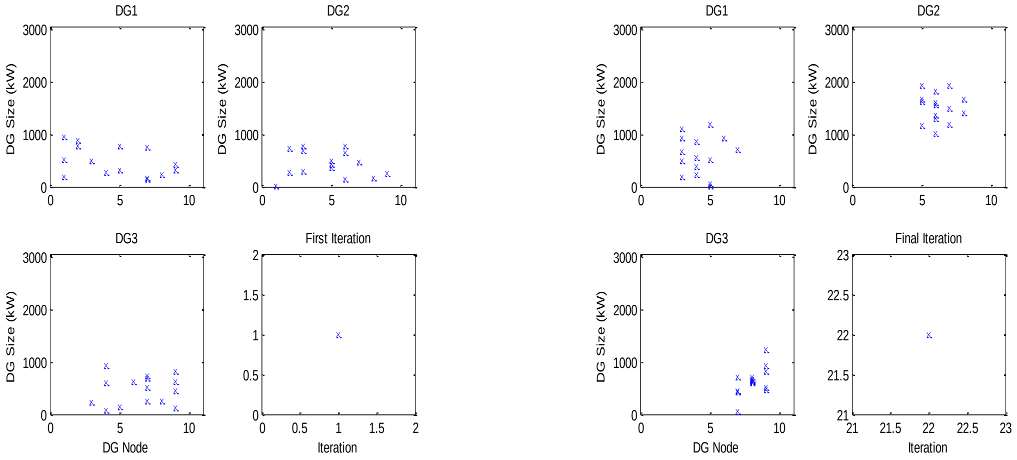
Table 5.29 PSO Based IEEE 13-Node Optimal Three DG Sizing & Placement

Simulation #	1	2	3	4	5	6
VDI	.3502	.3419	.3450	.5199	.3485	.3646
FCI	.2455	.2561	.2521	.0002	.2489	.2135
LI	.2468	.2885	.3179	.9995	.2489	.3642
RI	.1982	.1523	.1852	.8047	.2002	.1590
DGI	.2755	.2597	.3450	.0002	.2489	.1590
Theta	.0001	.0001	.0001	.0001	.0001	.0001
PSO DG1 Location	671	634	692	671	671	680
PSO DG1 Size	1404	293	1875	1	1451	4
% Diff Size	-6.0%	-5.0%	-4.0%	0.0%	-5.8%	0.0%
PSO DG2 Location	634	671	675	650	634	675
PSO DG2 Size	569	1696	556	651	236	1074
% Diff DG2 Size	-4.5%	-5.6%	-4.1%	0.0%	-5.0%	-6.6%
PSO DG3 Location	675	680	680	650	675	633
PSO DG3 Size	806	949	393	25	1085	1837
% Diff DG3 Size	-6.1%	-5.2%	-5.4%	0.0%	-5.4%	-3.3%
Total DG Size	2779	2938	2824	677	2772	2915
Total Max Limit DG Size	2946	2946	2946	2946	2946	2946
Total Time to find Optimal Solution (secs)	32.3	42.6	45.3	31.1	35.4	38.6
Total Simulation Time (secs)	47	57.2	48.9	35.8	49.1	52.4
kWLoss	31.5	39.5	47.0	101.2	32.2	45.8
kVarLoss	-67.5	-77.7	-83.7	-284.4	-67.9	-99.9



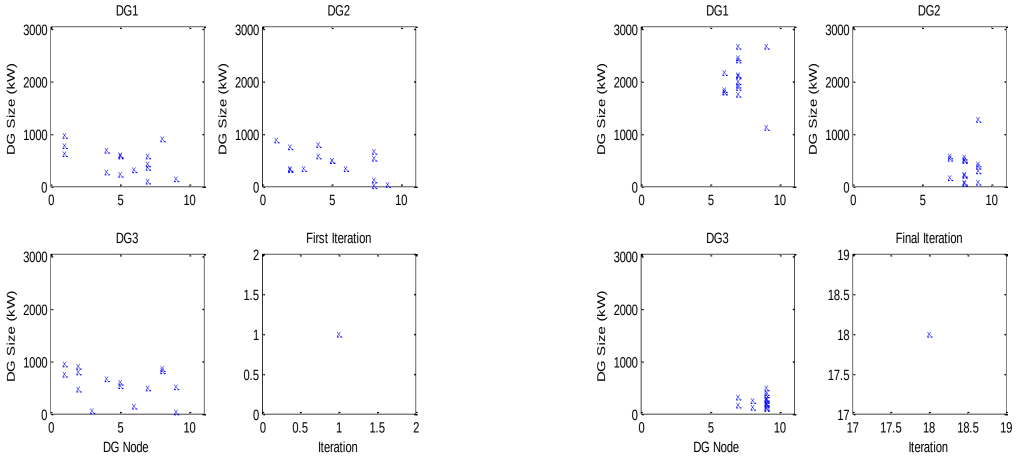
(a) (b)

Figure 5.19 Simulation #1 IEEE 13 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 17



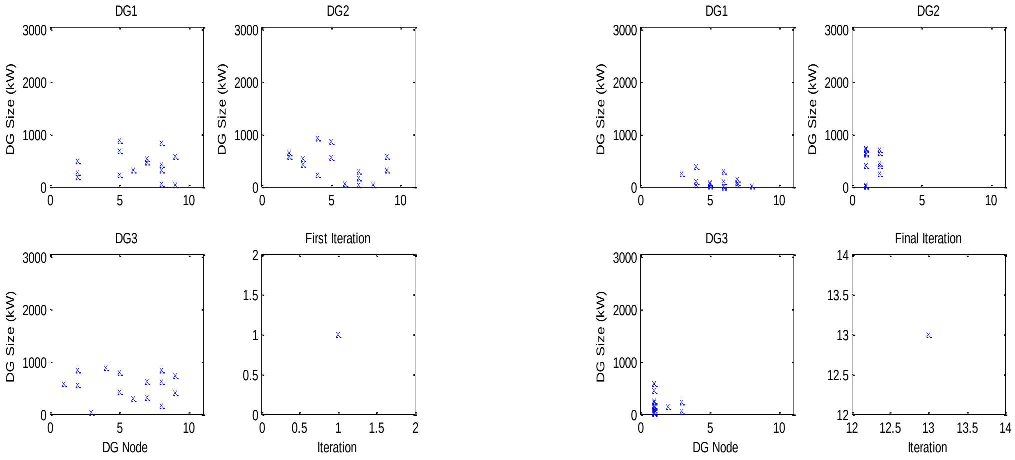
(a) (b)

Figure 5.20 Simulation #2 IEEE 13 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 22



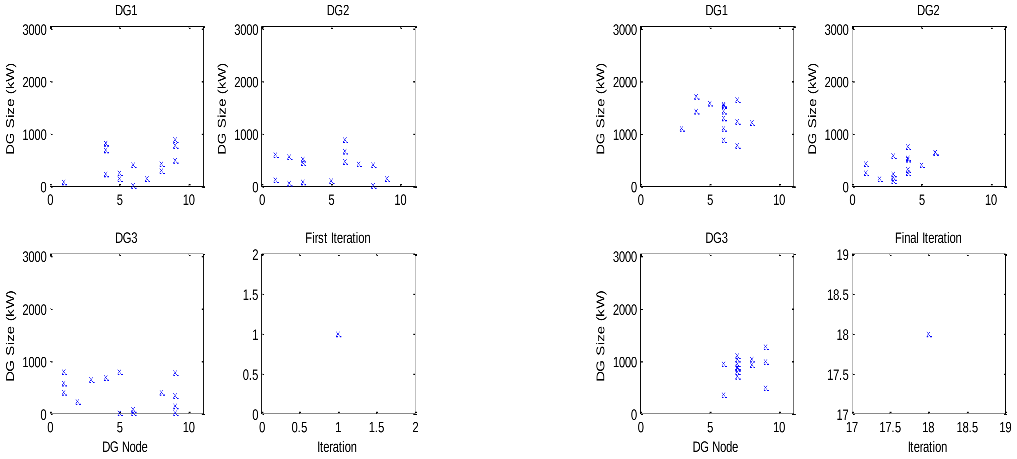
(a) (b)

Figure 5.21 Simulation #3 IEEE 13 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 18



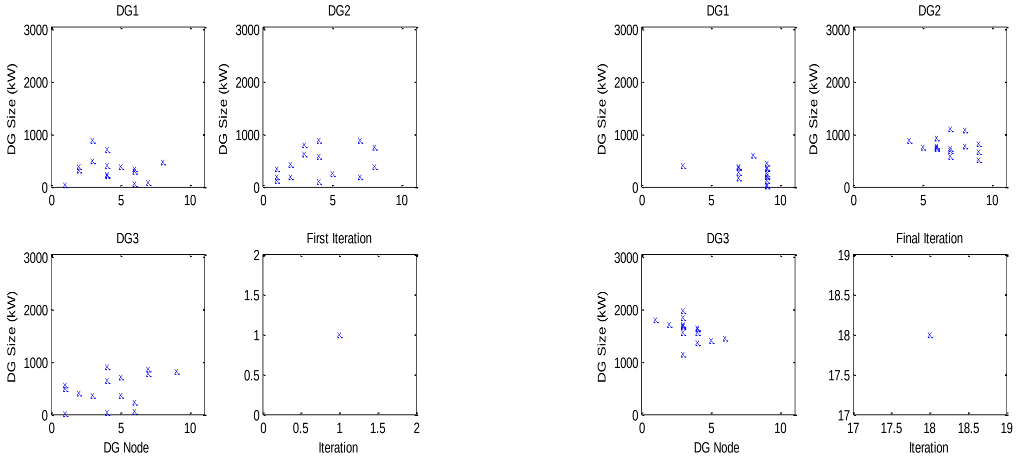
(a) (b)

Figure 5.22 Simulation #4 IEEE 13 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 13



(a) (b)

Figure 5.23 Simulation #5 IEEE 13 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 18



(a) (b)

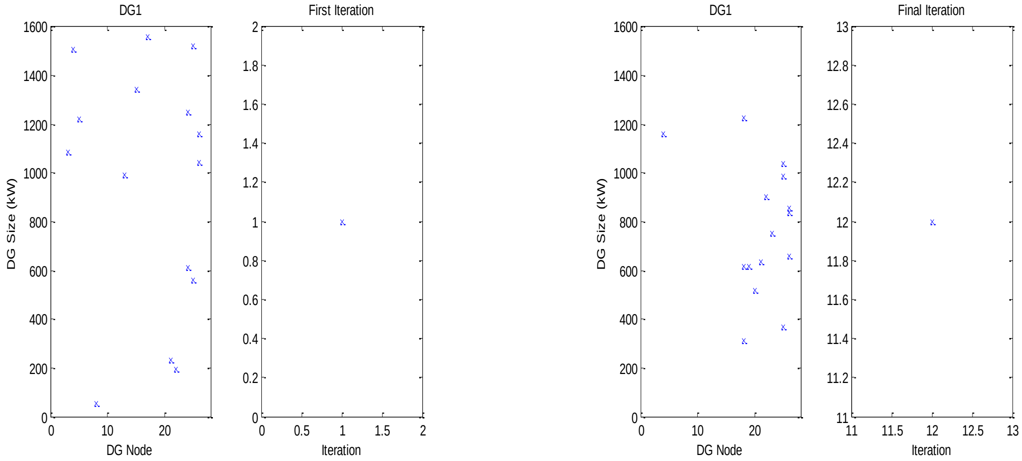
Figure 5.24 Simulation #6 IEEE 13 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 18

5.5.4.3 PSO Based IEEE 34-Node

5.5.4.3.1 IEEE 34-Node One DG Sizing & Placement

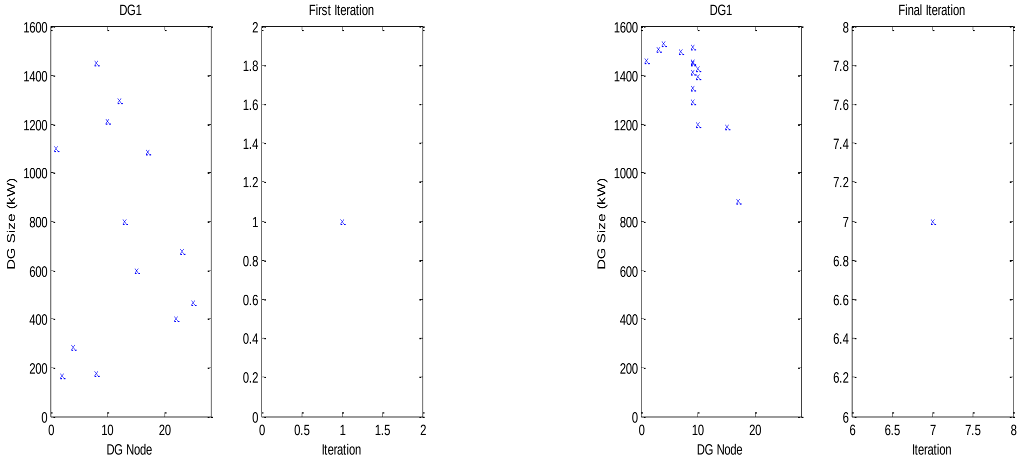
Table 5.30 PSO Based IEEE 34-Node Optimal One DG Sizing & Placement

Simulation #	1	2	3	4	5	6
VDI	.6157	.7505	.6164	1.3619	.7737	.9546
FCI	.1972	.1897	.1975	.0000	.1374	.2742
LI	.8122	.8557	.8145	1.000	.7756	.9244
RI	.5246	.1509	.5218	.7914	.7066	.1600
DGI	.6080	.4867	.6164	.0000	.7756	.1600
Theta	.0001	.0001	.0001	.0001	.0001	.0001
PSO DG1 Location	840	824	842	800	844	832
PSO DG1 Size	841	1502	846	369	519	1486
% Diff Size	-0.8%	7.3%	-1.1%	9.7%	-5.6%	6.5%
Total DG Size	841	1502	846	369	519	1486
Total Max Limit DG Size	1504	1504	1504	1504	1504	1504
Total Time to find Optimal Solution (secs)	30.8	10.4	14.7	23.8	24.2	28.5
Total Simulation Time (secs)	46.8	26.1	33.1	26.0	29.5	31.9
kWLoss	47.6	77.3	45.9	167.7	80.5	18.3
kVarLoss	-133.3	-127.5	-134.4	-47.8	-108.6	-160.1



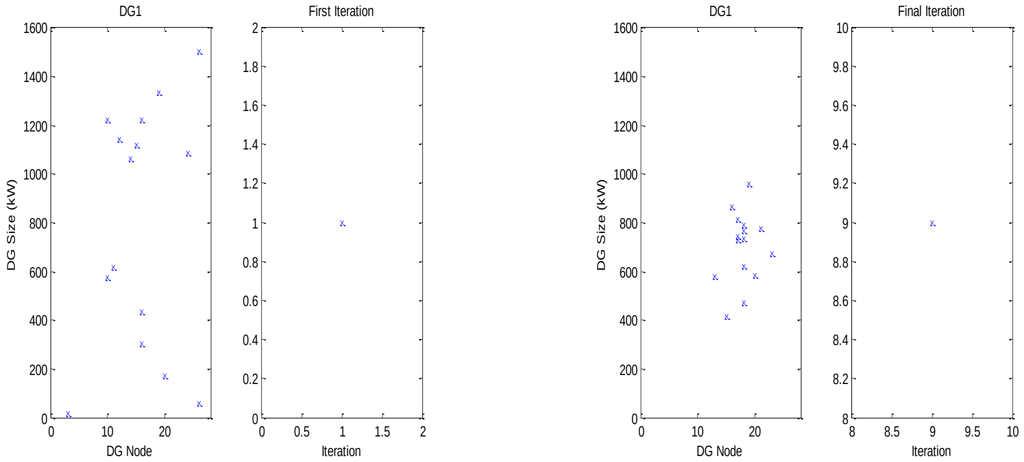
(a) (b)

Figure 5.25 Simulation #1 IEEE 34 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 12



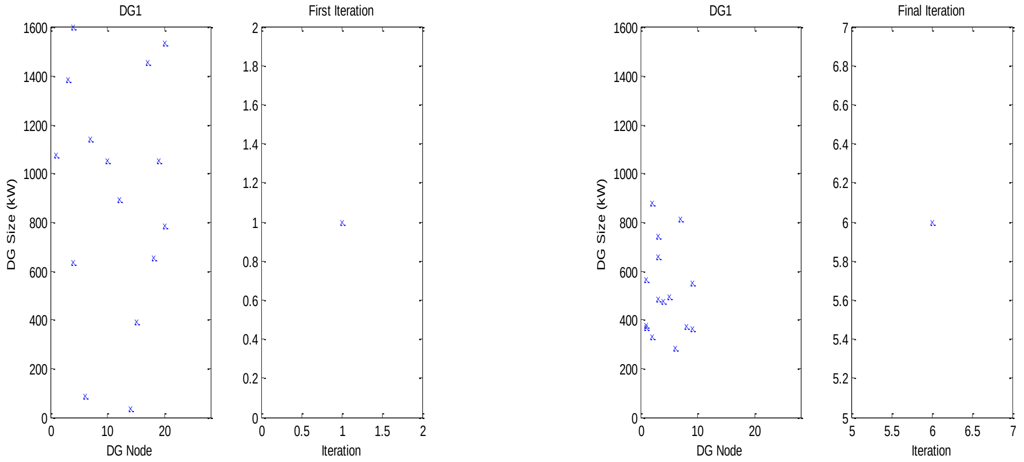
(a) (b)

Figure 5.26 Simulation #2 IEEE 34 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 7



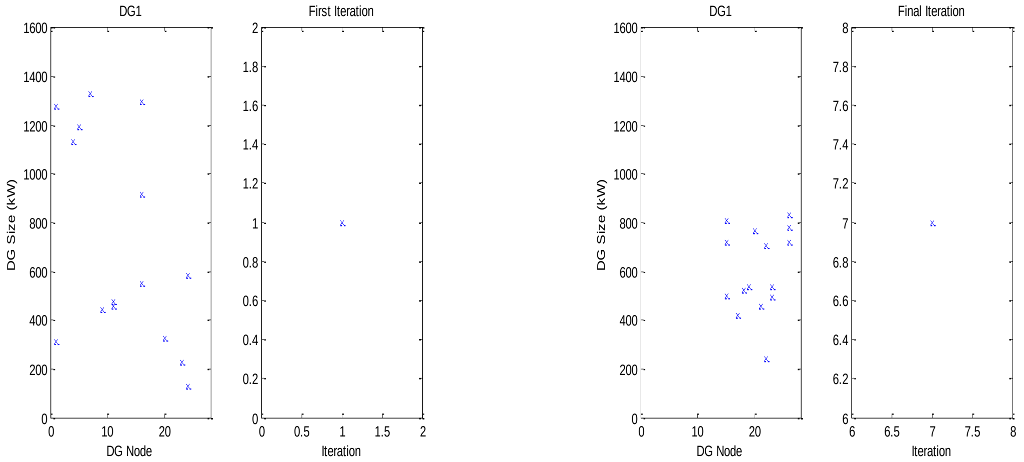
(a) (b)

Figure 5.27 Simulation #3 IEEE 34 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 9



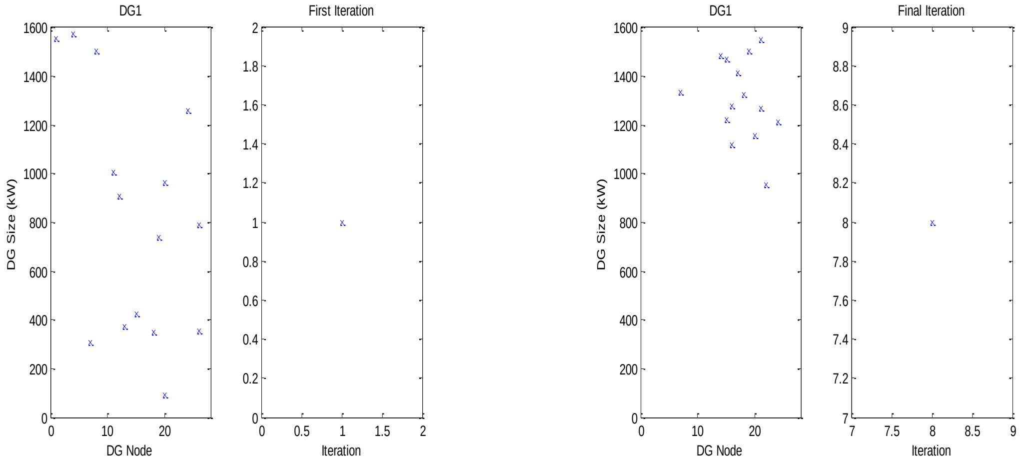
(a) (b)

Figure 5.28 Simulation #4 IEEE 34 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 6



(a) (b)

Figure 5.29 Simulation #5 IEEE 34 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 7



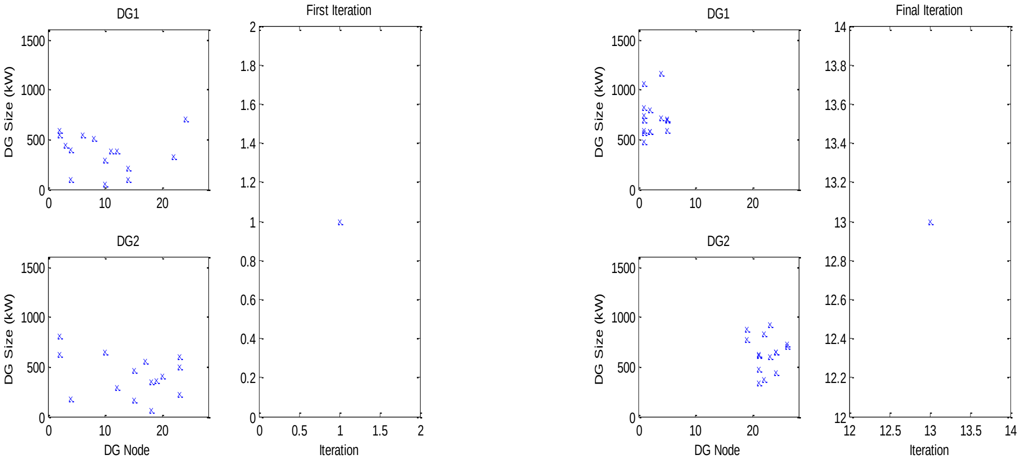
(a) (b)

Figure 5.30 Simulation #6 IEEE 34 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 8

5.5.4.3.2 IEEE 34-Node Two DG Sizing & Placement

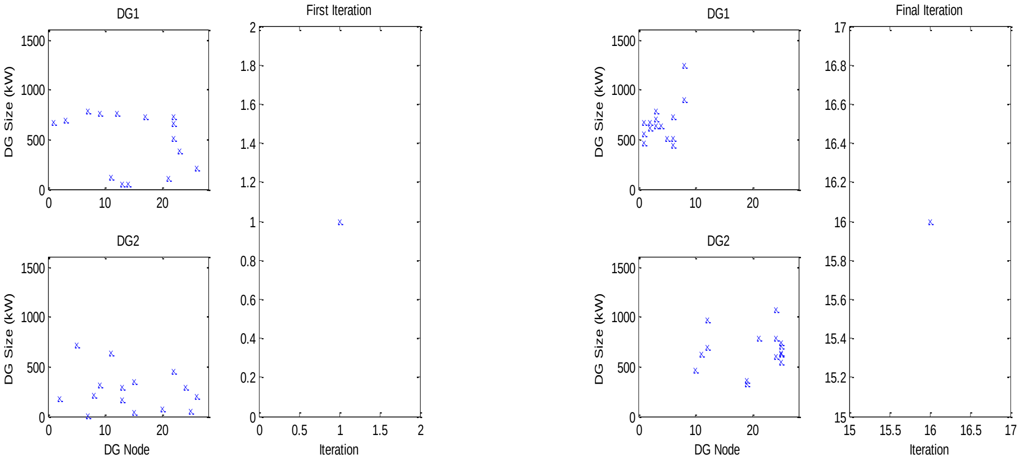
Table 5.31 PSO Based IEEE 34-Node Optimal Two DG Sizing & Placement

Simulation #	1	2	3	4	5	6
VDI	.6326	.6280	.6182	1.3619	.7704	1.042
FCI	.1844	.1878	.1988	.0000	.1384	.2836
LI	.7984	.8026	.8165	1.000	.7756	.9357
RI	.1622	.1775	.5138	.8666	.7049	.1504
DGI	.5528	.4490	.6182	.0000	.7756	.1504
Theta	.0001	.0001	.0001	.0001	.0001	.0001
PSO DG1 Location	800	800	832	800	836	834
PSO DG1 Size	719	668	277	118	211	650
% Diff Size	9.8%	9.7%	-0.7%	9.8%	-5.5%	7.2%
PSO DG2 Location	862	846	836	800	842	842
PSO DG2 Size	763	787	583	118	311	853
% Diff DG2 Size	-1.9%	-1.5%	-1.0%	9.8%	-5.6%	7.2%
Total DG Size	1482	1455	860	236	522	1503
Total Max Limit DG Size	1504	1504	1504	1504	1504	1504
Total Time to find Optimal Solution (secs)	33.3	43.6	16.9	29.7	29.4	25.2
Total Simulation Time (secs)	52.5	64.4	39.4	31.6	50.5	45.5
kWLoss	54.3	51.9	45.5	167.7	80.2	14.1
kVarLoss	-128.2	-129.9	-134.8	-47.8	-108.9	-162.5



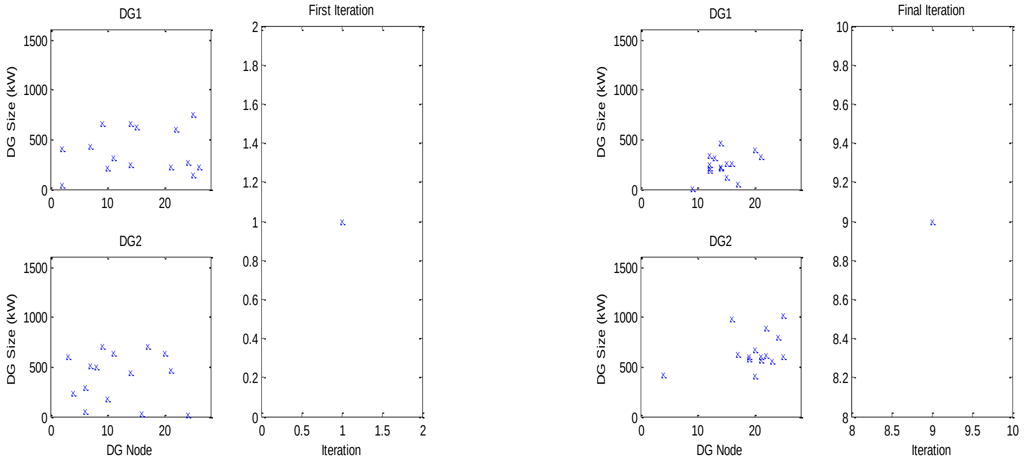
(a) (b)

Figure 5.31 Simulation #1 IEEE 34 PSO Based Optimal Two DG Sizing &Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 13



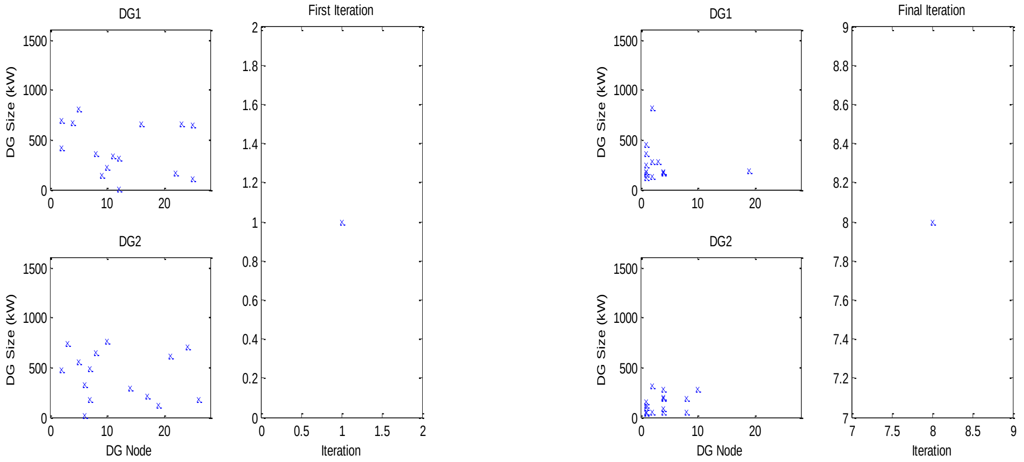
(a) (b)

Figure 5.32 Simulation #2 IEEE 34 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 16



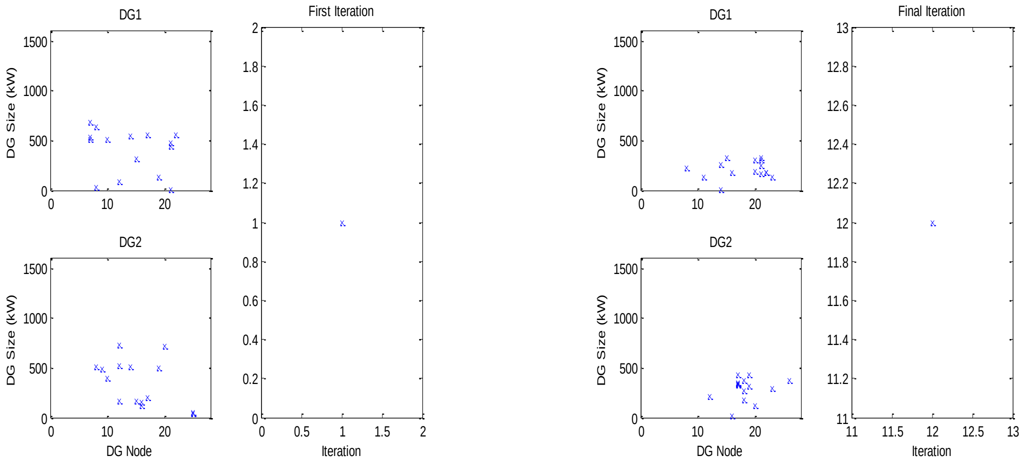
(a) (b)

Figure 5.33 Simulation #3 IEEE 34 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 9



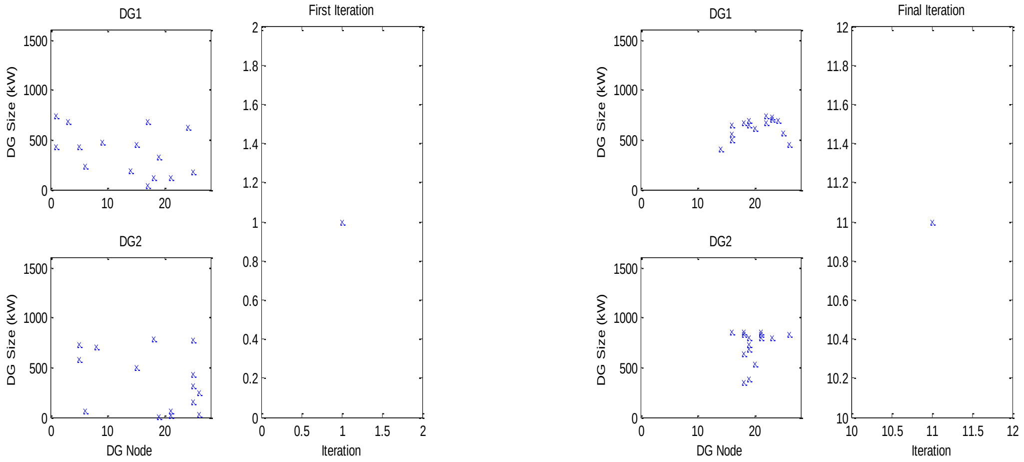
(a) (b)

Figure 5.34 Simulation #4 IEEE 34 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 8



(a) (b)

Figure 5.35 Simulation #5 IEEE 34 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 12



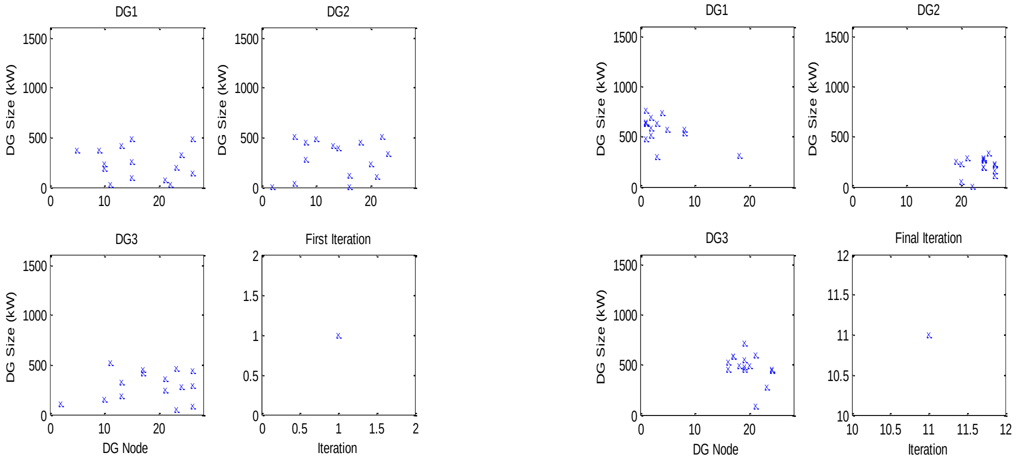
(a) (b)

Figure 5.36 Simulation #6 IEEE 34 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 11

5.5.4.3.3 IEEE 34-Node Three DG Sizing & Placement

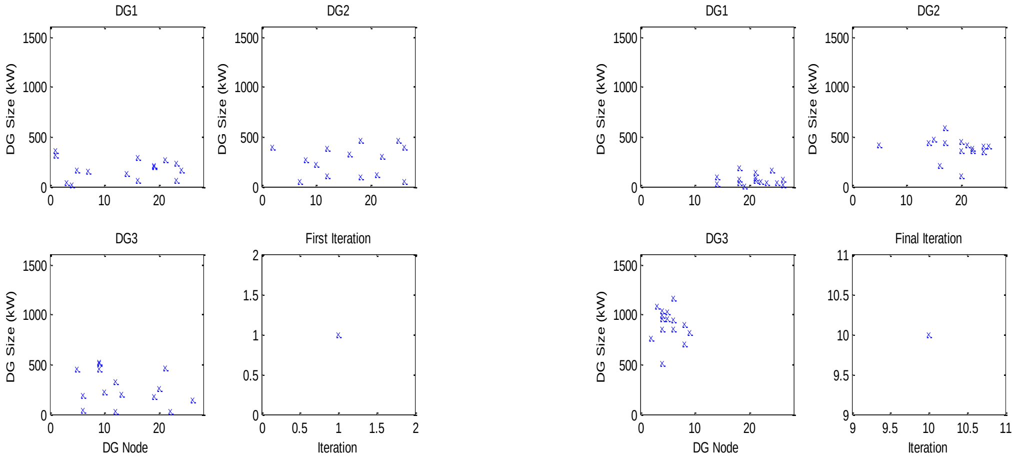
Table 5.32 PSO Based IEEE 34-Node Optimal Three DG Sizing & Placement

Simulation #	1	2	3	4	5	6
VDI	.6233	.7027	.6199	1.3619	.7491	.9980
FCI	.1921	.1511	.1953	.0000	.1428	.2787
LI	.8079	.7999	.8132	1.0000	.7756	.9346
RI	.1803	.1645	.5037	.9655	.6936	.1504
DGI	.5568	.4545	.6199	.0000	.7756	.1504
Theta	.0001	.0001	.0001	.0001	.0001	.0001
PSO DG1 Location	800	848	842	800	862	858
PSO DG1 Size	638	71	391	22	236	291
% Diff Size	9.7%	-4.1%	-1.3%	9.5%	-5.4%	6.4%
PSO DG2 Location	848	832	808	800	834	890
PSO DG2 Size	226	445	54	4	122	931
% Diff DG2 Size	-1.3%	-3.3%	7.7%	0.0%	-5.6%	6.8%
PSO DG3 Location	842	808	860	800	848	840
PSO DG3 Size	586	962	433	35	184	281
% Diff DG3 Size	-1.5%	9.0%	-1.1%	9.0%	-5.3%	6.2%
Total DG Size	1450	1478	878	61	542	1503
Total Max Limit DG Size	1504	1504	1504	1504	1504	1504
Total Time to find Optimal Solution (secs)	26.5	25.1	19.3	48.0	21.0	56.5
Total Simulation Time (secs)	48.6	47.0	42.6	58.0	40.9	78.4
kWLoss	48.8	71.5	46.8	167.7	77.5	14.6
kVarLoss	-132.2	-119.7	-133.8	-47.8	-110.7	-162.3



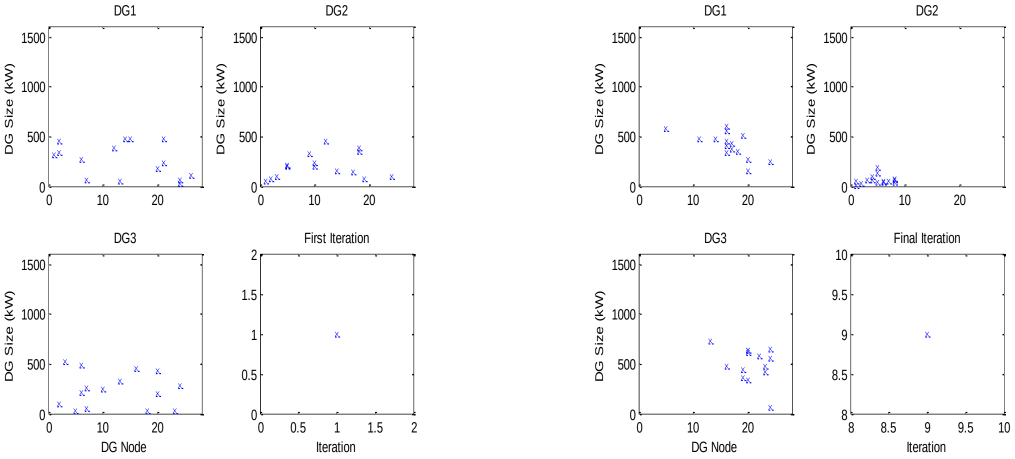
(a) (b)

Figure 5.37 Simulation #1 IEEE 34 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 11



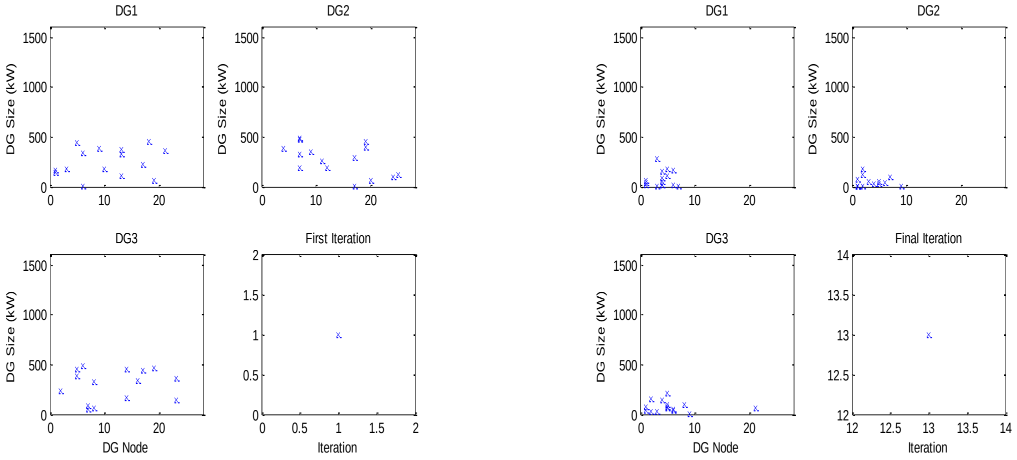
(a) (b)

Figure 5.38 Simulation #2 IEEE 34 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 10



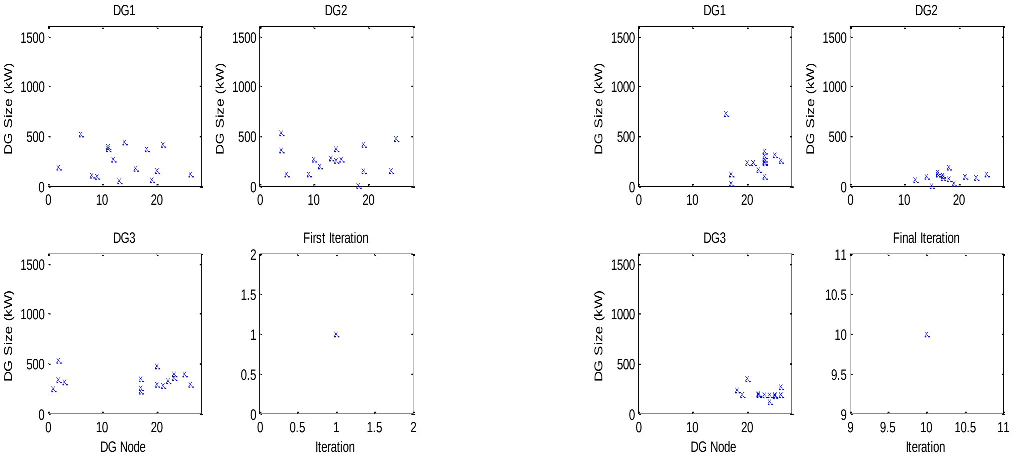
(a) (b)

Figure 5.39 Simulation #3 IEEE 34 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 9



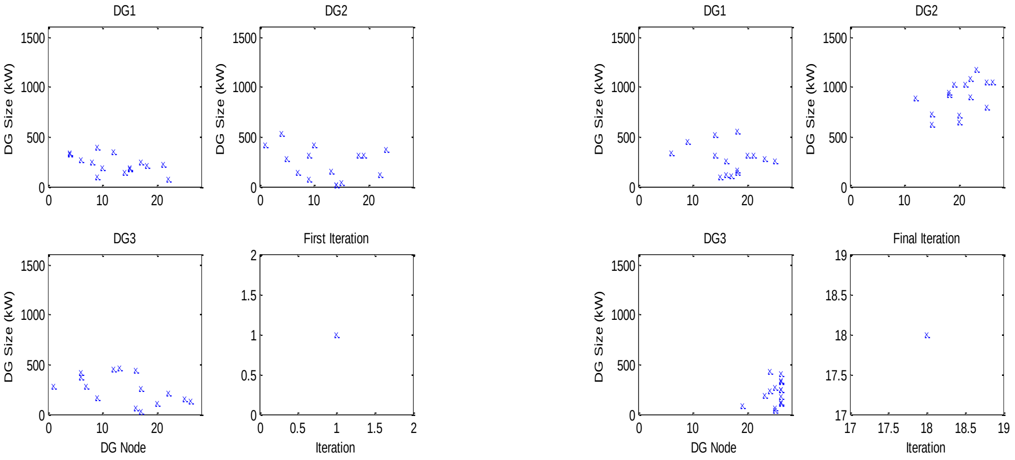
(a) (b)

Figure 5.40 Simulation #4 IEEE 34 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 13



(a) (b)

Figure 5.41 Simulation #5 IEEE 34 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 10



(a) (b)

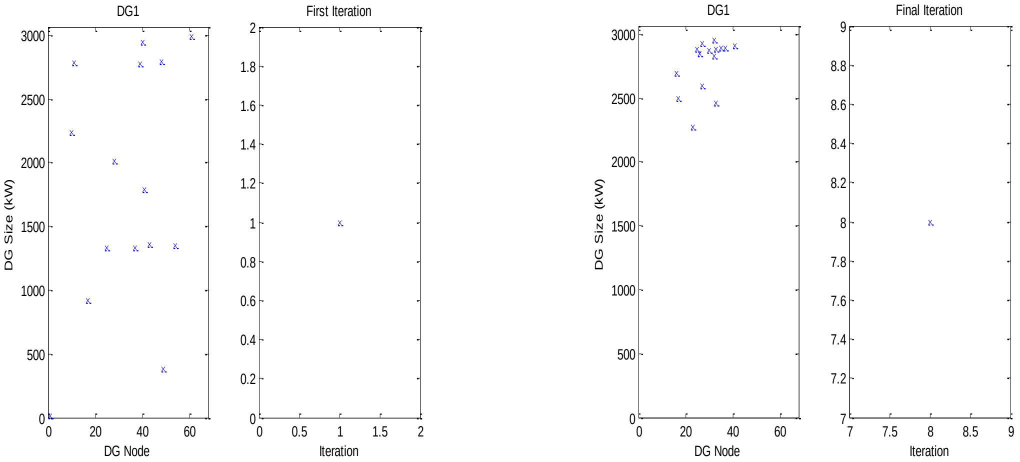
Figure 5.42 Simulation #6 IEEE 34 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 18

5.5.4.4 PSO Based IEEE 123-Node

5.5.4.4.1 IEEE 123-Node One DG Sizing & Placement

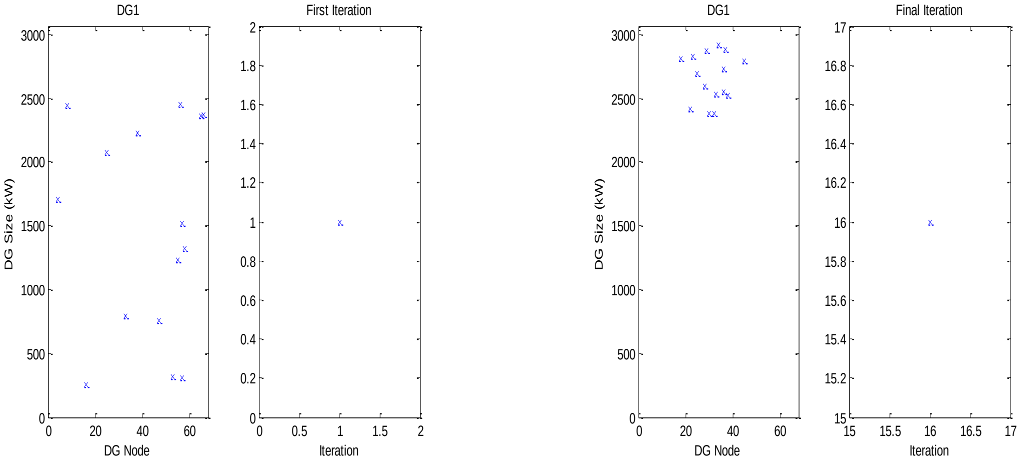
Table 5.33 PSO Based IEEE 123-Node Optimal One DG Sizing & Placement

Simulation #	1	2	3	4	5	6
VDI	1.3810	1.3882	1.3697	3.0202	1.7037	1.8452
FCI	.1738	.1730	.1774	.0000	.1375	.1003
LI	.3718	.3683	.5602	1.0000	.3479	.7192
RI	.1774	.1842	.1625	.9209	.4516	.1613
DGI	.6662	.5284	1.397	.0000	.3479	.1613
Theta	.0001	.0001	.0001	.0001	.0001	.0001
PSO DG1 Location	67	67	77	149	72	40
PSO DG1 Size	2871	2847	2923	276	1914	2927
% Diff Size	-1.2%	-1.2%	0.6%	0.0%	-2.9%	-1.3%
Total DG Size	2871	2847	2923	276	1914	2927
Total Max Limit DG Size	2967	2967	2967	2967	2967	2967
Total Time to find Optimal Solution (secs)	39.5	125.6	120.3	58.4	87.8	87.7
Total Simulation Time (secs)	98.2	182.2	176.6	120.7	118.9	142.6
kWLoss	34.4	34.1	50.6	87.1	32.1	63.7
kVarLoss	63.6	63.0	96.6	174.0	59.6	124.6



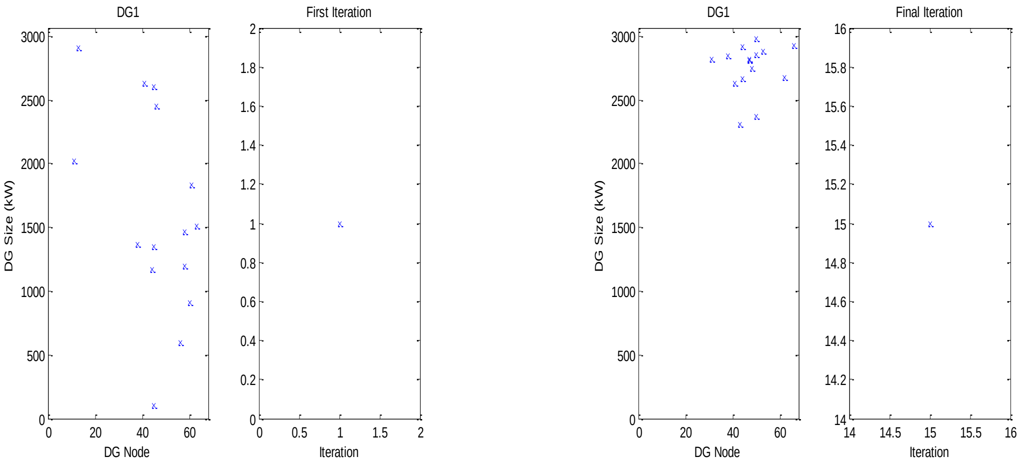
(a) (b)

Figure 5.43 Simulation #1 IEEE 123 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 8



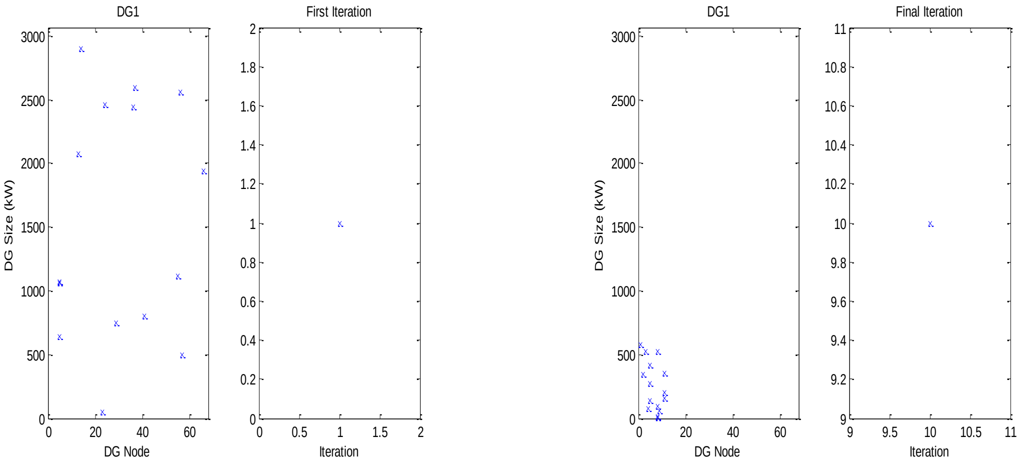
(a) (b)

Figure 5.44 Simulation #2 IEEE 123 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 16



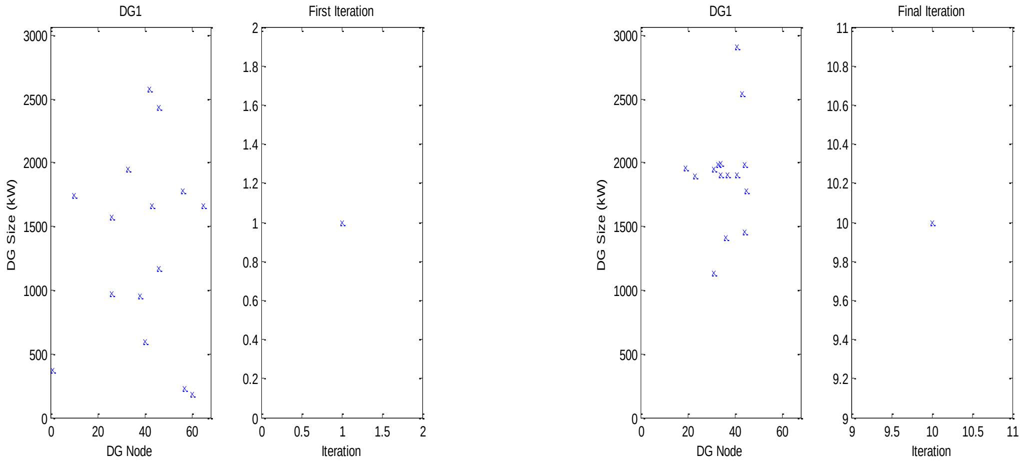
(a) (b)

Figure 5.45 Simulation #3 IEEE 123 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 15



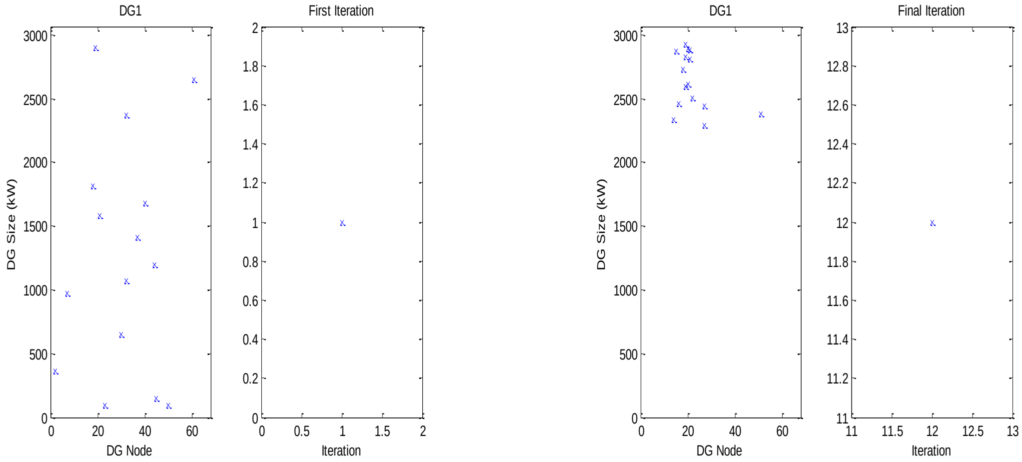
(a) (b)

Figure 5.46 Simulation #4 IEEE 123 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 10



(a) (b)

Figure 5.47 Simulation #5 IEEE 123 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 10



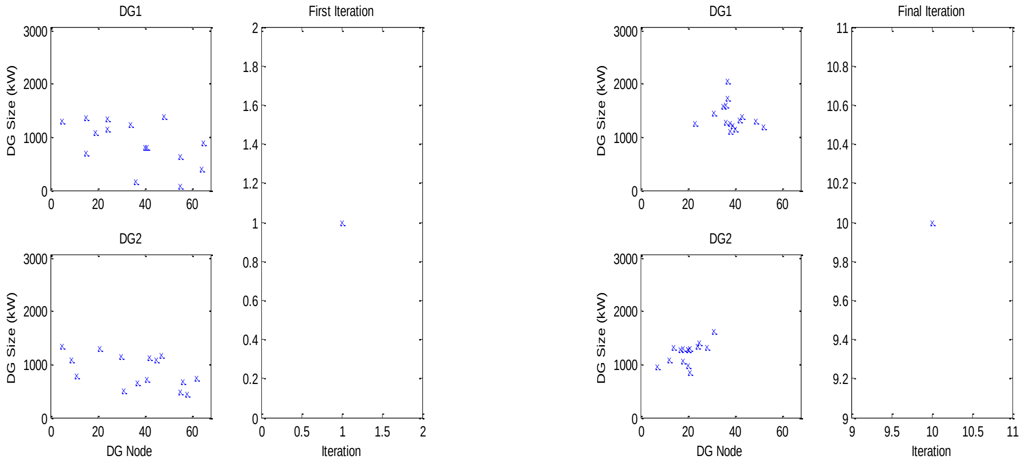
(a) (b)

Figure 5.48 Simulation #6 IEEE 123 PSO Based Optimal One DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 12

5.5.4.4.2 IEEE 123-Node Two DG Sizing & Placement

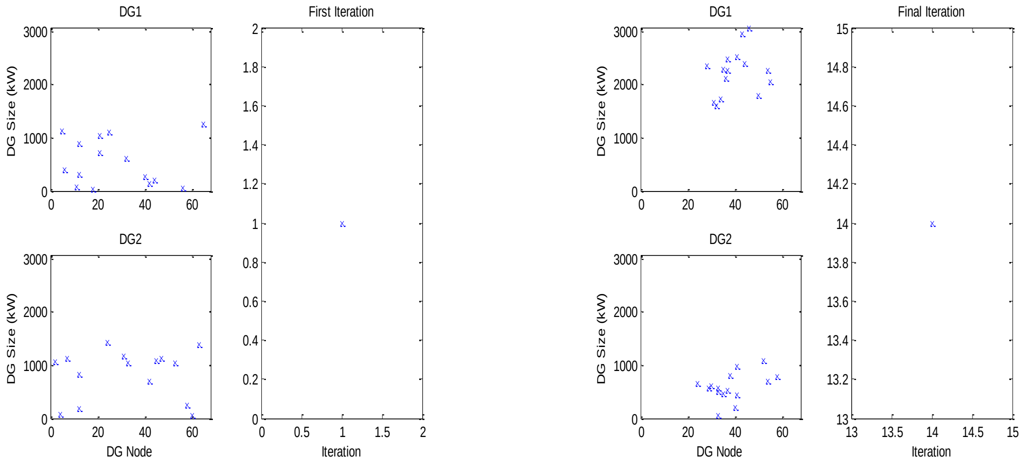
Table 5.34 PSO Based IEEE 123-Node Optimal Two DG Sizing & Placement

Simulation #	1	2	3*	4*	5	6
VDI	1.3863	1.3467	1.3401	3.0176	1.3615	1.3587
FCI	.1654	.1795	.1748	.0002	.1716	.1703
LI	.2262	.2777	.4096	.9978	.2239	.5057
RI	.1802	.1685	.1722	.6759	.1871	.1501
DGI	.6162	.4931	1.3401	.0002	.2239	.1501
Theta	.0001	.0001	.0001	.0001	.0001	.0001
PSO DG1 Location	72	72	49	149	49	99
PSO DG1 Size	1590	2431	787	1126	794	1645
% Diff Size	-2.7%	-1.3%	-3.5%	0.0%	-3.5%	-0.5%
PSO DG2 Location	40	48	81	52	67	65
PSO DG2 Size	1271	471	2102	5	2043	1321
% Diff DG2 Size	-2.8%	-4.0%	0.5%	0.0%	-2.3%	1.1%
Total DG Size	2861	2902	2889	1131	2837	2966
Total Max Limit DG Size	2967	2967	2967	2967	2967	2967
Total Time to find Optimal Solution (secs)	61.1	104.3	201.4	113.6	131.1	113.4
Total Simulation Time (secs)	124.1	167.3	268.9	124.7	190.3	180.9
kWLoss	21.8	26.3	37.6	89.9	21.7	53.7
kVarLoss	38.2	47.2	70.3	173.4	37.9	82.5



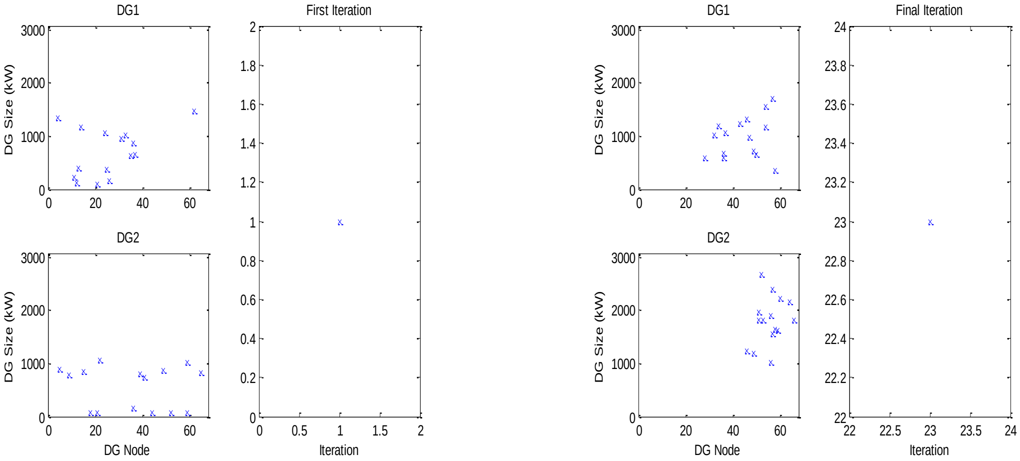
(a) (b)

Figure 5.49 Simulation #1 IEEE 123 PSO Based Optimal Two DG Sizing &Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 10



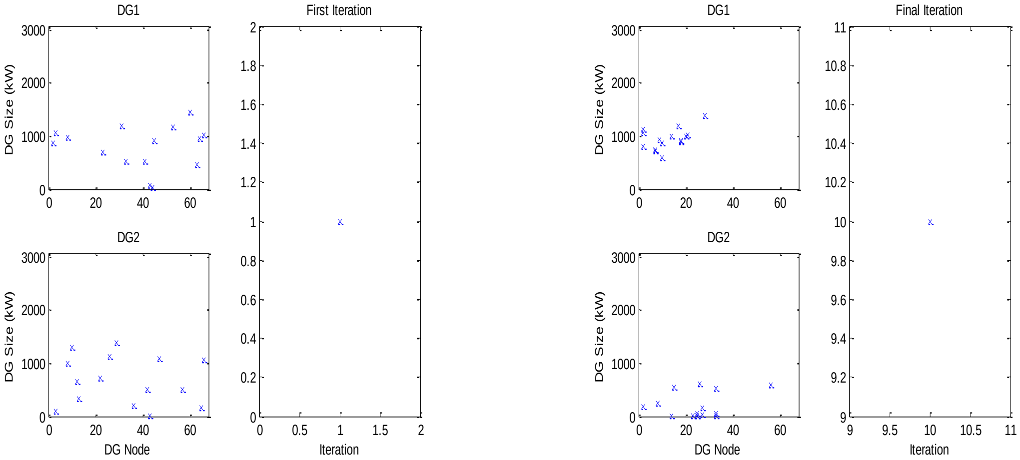
(a) (b)

Figure 5.50 Simulation #2 IEEE 123 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 14



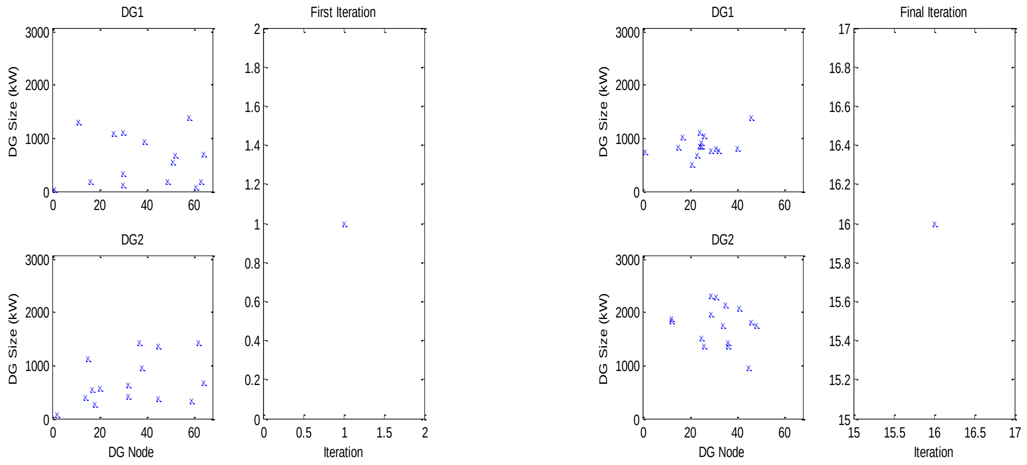
(a) (b)

Figure 5.51 Simulation #3 IEEE 123 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 23



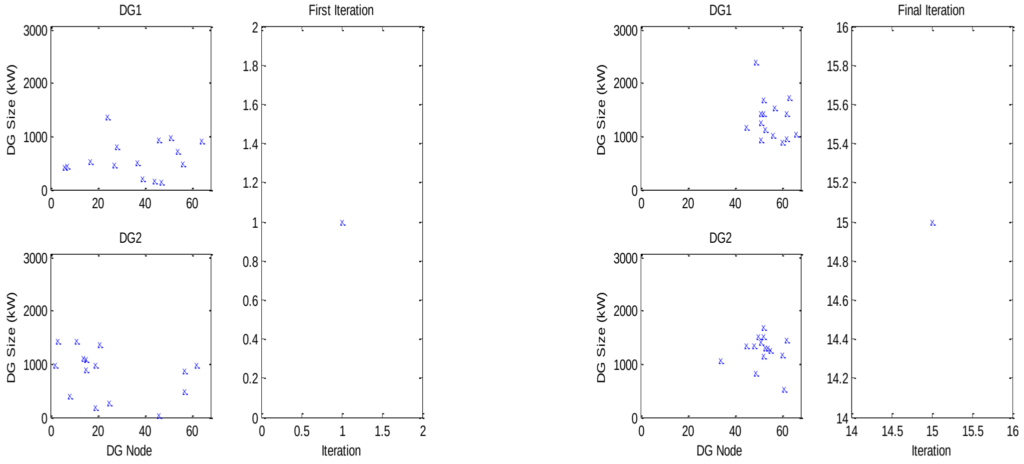
(a) (b)

Figure 5.52 Simulation #4 IEEE 123 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 10



(a) (b)

Figure 5.53 Simulation #5 IEEE 123 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 16



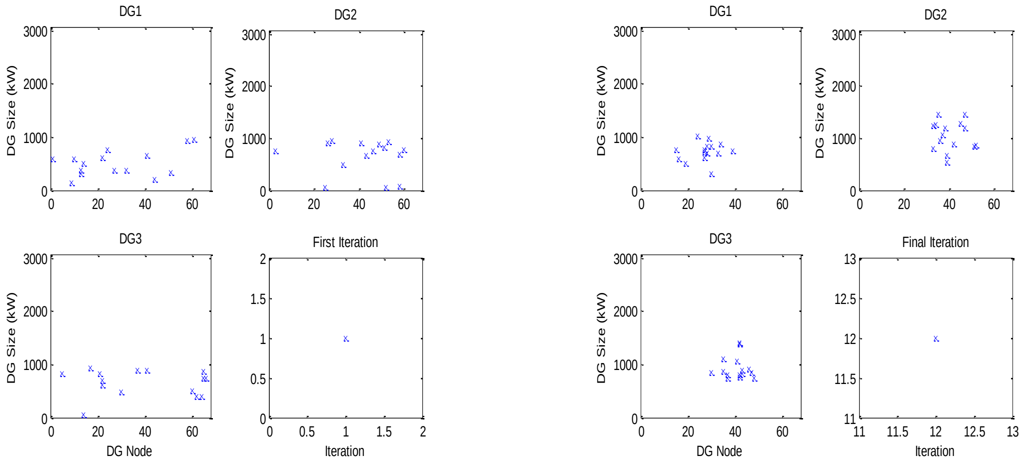
(a) (b)

Figure 5.54 Simulation #6 IEEE 123 PSO Based Optimal Two DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 15

5.5.4.4.3 IEEE 123-Node Three DG Sizing & Placement

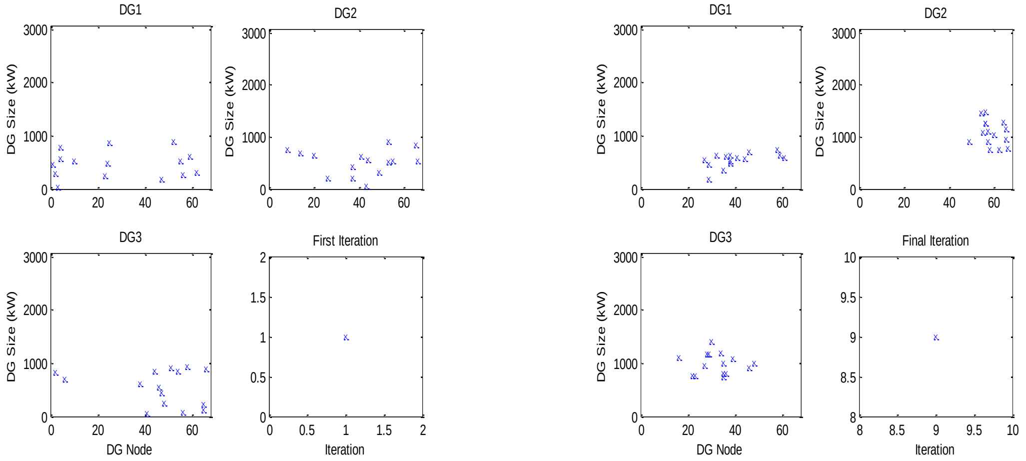
Table 5.35 PSO Based IEEE 123-Node Optimal Three DG Sizing & Placement

Simulation #	1	2	3	4	5	6
VDI	1.3515	1.3382	1.3254	3.0202	1.4616	2.1167
FCI	.1729	.1808	.1835	.0000	.1578	.0663
LI	.2109	.2659	.3369	1.0000	.2220	.5400
RI	.1797	.1751	.1625	.9797	.2481	.1542
DGI	.5997	.4900	1.3254	.0000	.2220	.1542
Theta	.0001	.0001	.0001	.0001	.0001	.0001
PSO DG1 Location	47	50	82	150	77	7
PSO DG1 Size	833	617	1448	4	631	1051
% Diff Size	-3.4%	-3.7%	0.7%	-0.0%	-2.5%	-1.2%
PSO DG2 Location	76	81	51	150	160	8
PSO DG2 Size	1193	1095	567	1	1250	669
% Diff DG2 Size	-2.2%	-0.2%	-3.6%	0.0%	-2.8%	-1.6%
PSO DG3 Location	64	67	197	150	42	18
PSO DG3 Size	837	1167	908	66	743	1232
% Diff DG3 Size	-1.7%	-2.0%	-1.9%	0.0%	-3.6%	-3.1%
Total DG Size	2863	2879	2923	71	2624	2952
Total Max Limit DG Size	2967	2967	2967	2967	2967	2967
Total Time to find Optimal Solution (secs)	86.0	56.6	121.7	187.7	145.2	167.1
Total Simulation Time (secs)	151.7	113.7	184.7	242.2	199.8	236.9
kWLoss	21.5	25.3	31.9	87.1	21.4	48.4
kVarLoss	34.9	45.1	57.6	174.0	37.5	93.3



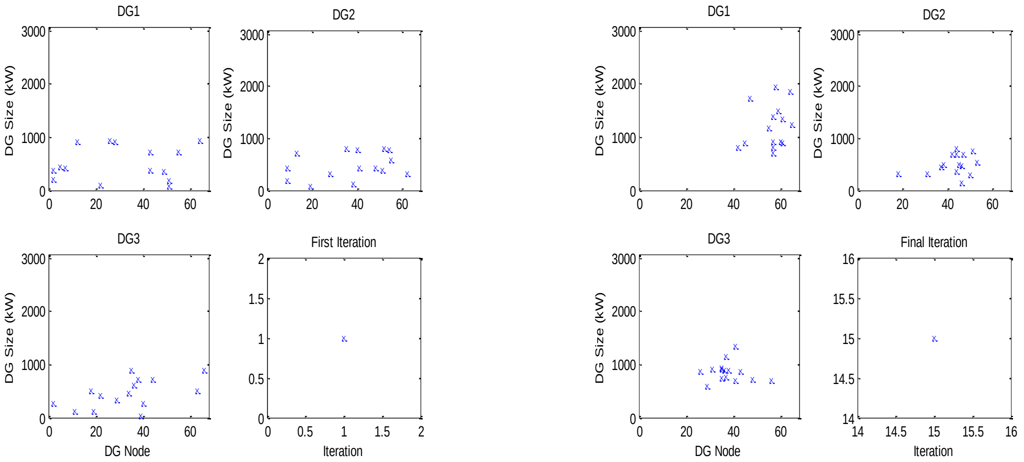
(a) (b)

Figure 5.55 Simulation #1 IEEE 123 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 12



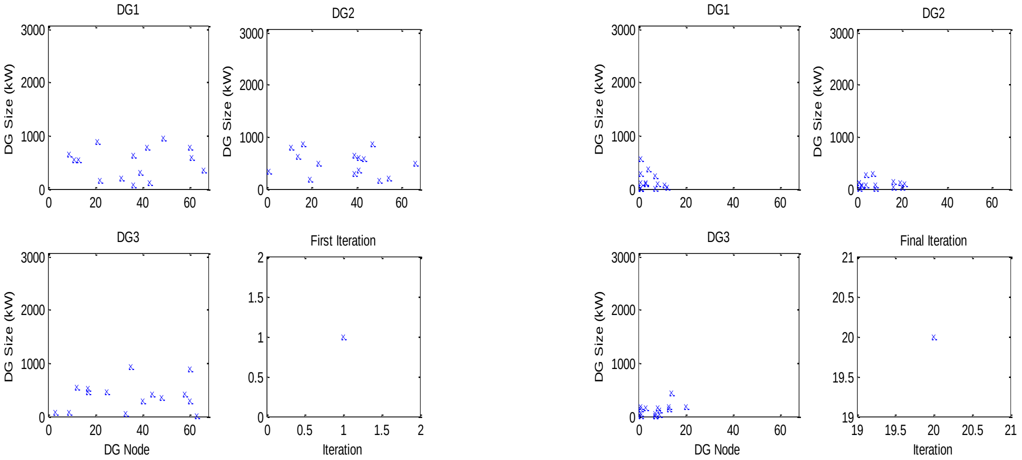
(a) (b)

Figure 5.56 Simulation #2 IEEE 123 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 9



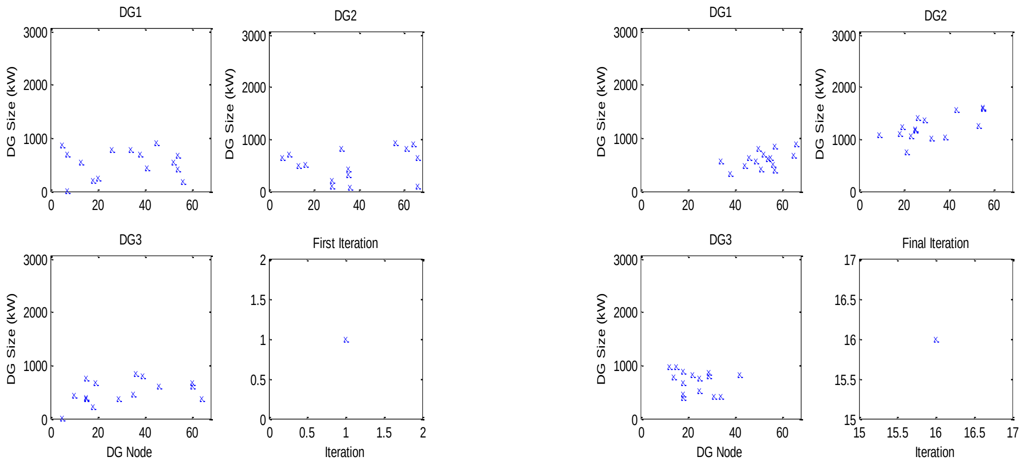
(a) (b)

Figure 5.57 Simulation #3 IEEE 123 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 15



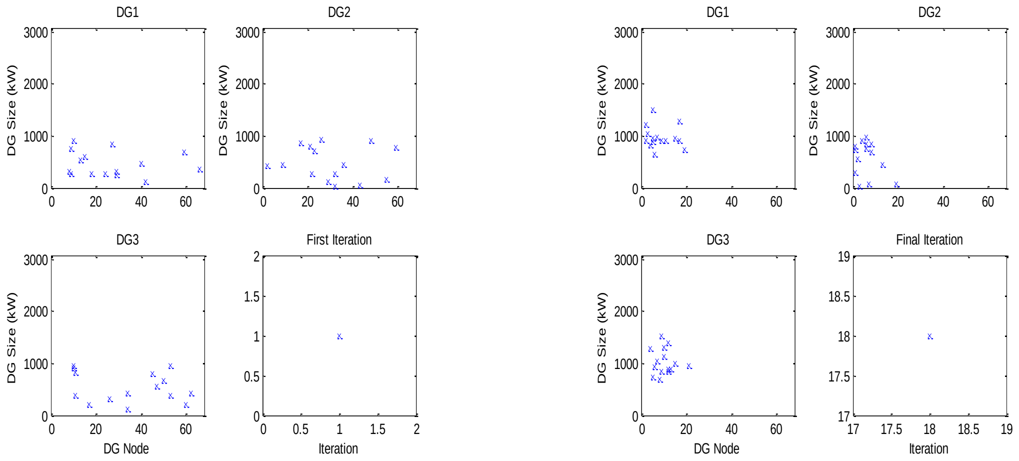
(a) (b)

Figure 5.58 Simulation #4 IEEE 123 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 20



(a) (b)

Figure 5.59 Simulation #5 IEEE 123 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 16



(a) (b)

Figure 5.60 Simulation #6 IEEE 123 PSO Based Optimal Three DG Sizing & Placement Search Space, (a) First Iteration = 1 (b) Final Iteration = 18

5.6 Optimal DG Sizing and Placement Comparative Analysis

The Modified Rule of Thumb, Iteration Based Approach and the PSO Based Approach will be compared in the following section for the IEEE 13, IEEE 34 and IEEE 123 Node Test Cases. Like most optimization problems, the optimal DG sizing and placement problem has two primary trade-offs: speed and accuracy. Certain parameters are adjusted to ensure that the global or near global solution is found by the algorithm. The speed of either method may be improved by adjusting various simulation parameters; the incremental DG size for the iteration based or by adjusting the following parameters in the PSO approach: Theta, velocity clamp, inertia weight, constriction factors (i.e. Theta = .001 versus Theta = .0001). In analyzing the performance of the power system, engineers are primarily concerned with the overall voltage profile, overall system losses and fault current conditions, all of which contribute to the reliability of the system. Typically, the optimal placement for a distributed generator is near the maximum load center. Since Simulation #1 weight-factors represents a more practical evaluation criteria used to analyze the impact of DG on a power system, the results of the various test cases for Simulation #1 will be analyzed in the following section.

5.6.1.1 IEEE 13-Node Optimal DG Sizing & Placement Analysis

The IEEE 13 Node Distribution Feeder is a relatively small, but highly loaded system with a nominal voltage of 4.16 kV. The IEEE 13 system provides the opportunity to examine the impact of DG on a condensed distribution system. Table 5.36 compares the results of the optimal DG sizing and placement on the IEEE 13 Node Test Case. As seen in Table 5.36, the dominant location obtained in the simulation results is Node 671. The Iteration and PSO based approach provides relatively the same results for the single DG application. The generator size at Node 671 is the largest in the single, two and three

DG application. The PSO based approach for the single and two DG application seems to provide indication of a uniform convergence on the optimal size and location as seen in Figure 5.7(b) and Figure 5.13(b). For the three DG application, Figure 5.19(b) illustrates a moderate convergence of the particles on the optimal solution. According to the results, the best system performance using for Simulation #1 occurs with the three generator scenario, where DGI = .2755.

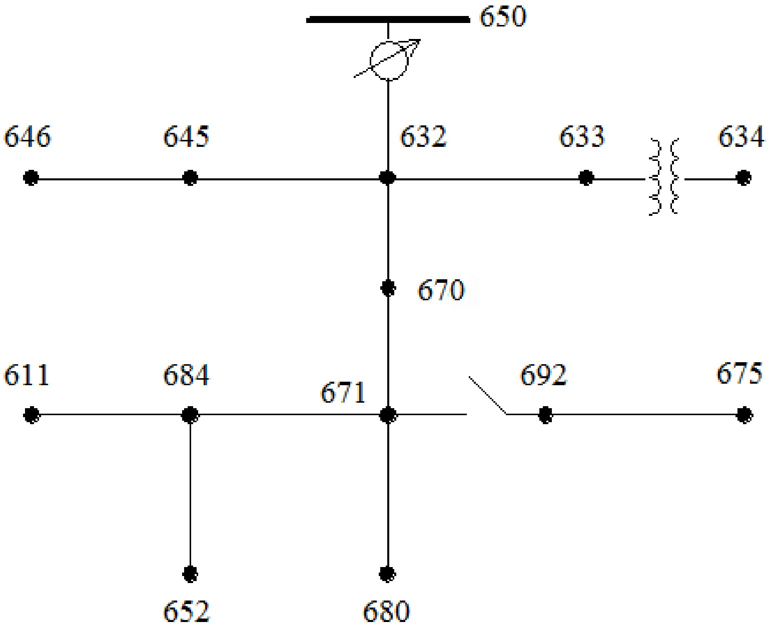


Figure 5.61 Single Line Diagram of the IEEE 13-Node Test System [4]

Table 5.36 IEEE 13-Node Optimal DG Sizing & Placement Comparison: Simulation#1

Solution Method	Modified Rule of Thumb1 1 DG	Modified Rule of Thumb2 2 DG	Modified Rule of Thumb2 3 DG	Iteration 1DG	PSO1 1 DG	PSO2 2 DG	PSO3 3 DG
VDI	-------	-------	-------	.3485	.3492	.3480	.3502
FCI	-------	-------	-------	.2484	.2477	.2494	.2455
LI	-------	-------	-------	.2839	.2840	.2613	.2468
RI	-------	-------	-------	.1950	.1994	.2011	.1982
DGI	-------	-------	-------	.2878	.2887	.2808	.2755
PSO DG1 Location	-------	-------	-------	671	671	675	671
PSO DG1 Size	2507	1890	1582	2790	2775	628	1404
PSO DG2 Location	-------	-------	-------	-------	-------	671	634
PSO DG2 Size	-------	990	829	-------	-------	2141	569
PSO DG3 Location	-------	-------	-------	-------	-------	-------	675
PSO DG3 Size	-------	-------	562	-------	-------	-------	806
Total DG Size	2507	2880	2973	2790	2775	2769	2779
Total Max Limit DG Size	2946	2946	2946	2946	2946	2946	2946
Total Simulation Time (secs)	-------	-------	-------	139.9	31.2	59.9	47.0
kWLoss	-------	-------	-------	39.8	39.8	34.1	31.5
kVarLoss	-------	-------	-------	-75.9	-75.9	-71.2	-67.5
kVALoss	-------	-------	-------	85.7	85.7	78.9	74.4

5.6.1.2 IEEE 34-Node Optimal DG Sizing & Placement Analysis

The IEEE 34 test system is a long and lightly loaded system. The majority of the system load is located farther away from the substation. Table 5.37 compares the results of the optimal DG sizing and placement on the IEEE 34 Node Test Case. Again, the Iteration and PSO based approach provides relatively the same results for the single DG application. The one DG application results seem inconsistent with the results obtained from the two and three DG applications. In analyzing Figure 5.25(b), the particles do not demonstrate a dominant convergence pattern. Figures 5.31(b) and 5.37(b) provide a more uniform convergence of the particles in search for the optimal solution. As seen in Table 5.37, the simulation doesn't provide a dominant node location, but rather provides a dominant region for an optimal location. The dominant region is toward the end of the feeder, where the majority of the system load is located. According to the results, the best system performance occurs with the two generator scenario due primarily to an improvement in system losses, where LI = .1844 and DGI = .5528.

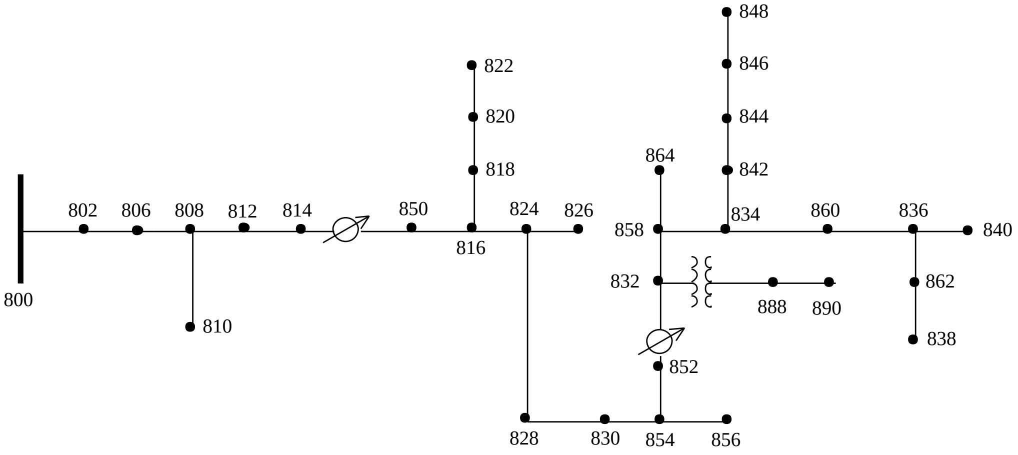


Figure 5.62 Single Line Diagram of the IEEE 34-Node Test System [4]

Table 5.37 IEEE 34-Node Optimal DG Sizing & Placement Comparison: Simulation#1

Solution Method	Modified Rule of Thumb1 1 DG	Modified Rule of Thumb2 2 DG	Modified Rule of Thumb2 3 DG	Iteration 1DG	PSO1 1 DG	PSO2 2 DG	PSO3 3 DG
VDI	-------	-------	-------	.6157	.6157	.6326	.6233
FCI	-------	-------	-------	.1979	.1972	.1844	.1921
LI	-------	-------	-------	.8126	.8122	.1844	.8079
RI	-------	-------	-------	.5235	.5246	.1622	.1803
DGI	-------	-------	-------	.6081	.6080	.5528	.5568
PSO DG1 Location	-------	-------	-------	840	840	800	800
PSO DG1 Size	1280	965	808	843	841	719	638
PSO DG2 Location	-------	-------	-------	-------	-------	862	848
PSO DG2 Size	-------	505	423	-------	-------	763	226
PSO DG3 Location	-------	-------	-------	-------	-------	-------	842
PSO DG3 Size	-------	-------	287	-------	-------	-------	586
Total DG Size	1280	1470	1518	843	841	1482	1450
Total Max Limit DG Size	1504	1504	1504	1504	1504	1504	1504
Total Simulation Time (secs)	-------	-------	-------	331.3	46.8	52.5	48.6
kWLoss	-------	-------	-------	47.5	47.6	54.3	48.8
kVarLoss	-------	-------	-------	-133.4	-133.3	-128.2	-132.2
kVALoss	-------	-------	-------	141.6	141.5	139.2	140.9

5.6.1.3 IEEE 123-Node Optimal DG Sizing & Placement Analysis

The IEEE 123 Node Distribution Feeder is relatively large with modest system loading and a nominal voltage of 4.16 kV. Table 5.38 compares the results of the optimal DG sizing and placement on the IEEE 123 Node Test Case. The total optimal DG size for all applications provides consistent solutions. Again, the Iteration and PSO based approach provides relatively the same location and size for the single DG application. Of course, the size of the system drastically increases the simulation time for the iteration based approach. Figures 5.43(b), 5.49(b) and 5.55(b) provide a more uniform convergence on the optimal solution. As seen in Table 5.38, the simulation doesn’t provide a particular dominant node location, but rather provides several dominant regions for an optimal location (i.e. Region 1: Nodes 67, 72, 76; Region 2: Nodes 40, 47; Region 3: Node 64). The dominant regions are located in relatively high load concentration area. According to the results, the best system performance occurs with the three generator scenario, where DGI = .5997

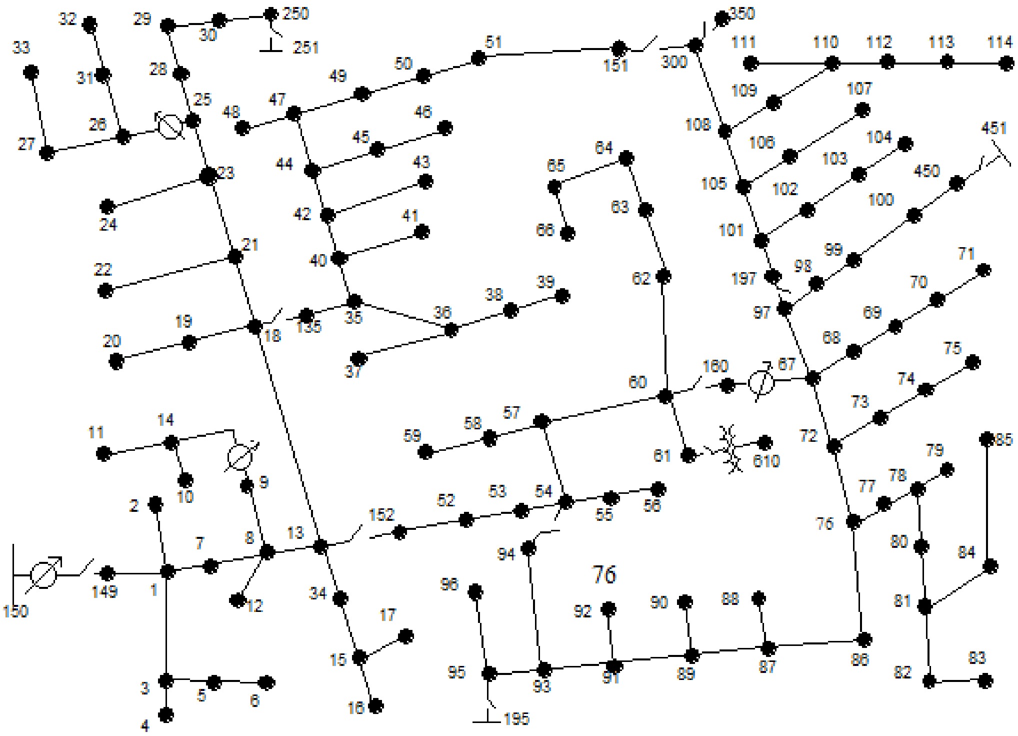


Figure 5.63 Single Line Diagram of the IEEE 123-Node Test System [4]

Table 5.38 IEEE 123-Node Optimal DG Sizing & Placement Comparison: Simulation#1

Solution Method	Modified Rule of Thumb1 1 DG	Modified Rule of Thumb2 2 DG	Modified Rule of Thumb2 3 DG	Iteration 1DG	PSO1 1 DG	PSO2 2 DG	PSO3 3 DG
VDI	-------	-------	-------	1.358	1.3810	1.3863	1.3515
FCI	-------	-------	-------	.1765	.1738	.1654	.1729
LI	-------	-------	-------	.3833	.3718	.2262	.2109
RI	-------	-------	-------	.1562	.1774	.1802	.1797
DGI	-------	-------	-------	.6596	.6662	.6162	.5997
PSO DG1 Location	-------	-------	-------	67	67	72	47
PSO DG1 Size	2524	1903	1593	2945	2871	1590	833
PSO DG2 Location	-------	-------	-------	-------	-------	40	76
PSO DG2 Size	-------	997	835	-------	-------	1271	1193
PSO DG3 Location	-------	-------	-------	-------	-------	-------	64
PSO DG3 Size	-------	-------	565	-------	-------	-------	837
Total DG Size	2524	2900	2993	2945	2871	2861	2863
Total Max Limit DG Size	2967	2967	2967	2967	2967	2967	2967
Total Simulation Time (secs)	-------	-------	-------	5702	98.2	124.1	151.7
kWLoss	-------	-------	-------	35.4	34.4	21.8	21.5
kVarLoss	-------	-------	-------	-65.6	63.6	38.2	34.9
kVALoss	-------	-------	-------	74.5	72.3	43.9	40.9

5.7 Summary

This chapter tested the Multi-objective Optimal DG Sizing and Placement algorithm on three test cases, IEEE 13-Node, 34-Node and 123-Node. The developed indices were able to properly assess the impact of distributed generation by calculating the following parameters for each DG configuration: voltage deviation, fault current contributions, system losses and system reliability. The weights on the indices were varied to test the ability of the algorithm to determine the optimal size and placement of the DG based on different evaluation criterion. The particle swarm optimization technique was utilized to improve the overall performance and speed of the optimal DG sizing and placement algorithm. This chapter also tested the ability of the Modified Rule of Thumb to determine the optimal size of the DG based on various evaluation criteria.

The developed indices and PSO technique successfully solved the optimal DG sizing and placement problem for the IEEE 13-Node, 34-Node and 123-Node Test Cases. The multi-objective index proved to be computational efficient and accurately evaluated the impact of distributed generation on the power system. The results provided valuable information about the system response to single and multiple DG units. The Modified Rule of Thumb also provided adequate approximations under certain system conditions.

5.8 REFERENCES

[1] Roger Dugan, “Reference Guide: The Open Distribution System Simulator (OpenDSS),” Electric Power Research Institute, 2009.

[2] W. H. Kersting, "Radial distribution test feeders," in *Power Engineering Society Winter Meeting, 2001. IEEE*, 2001, pp. 908-912 vol. 2.

[3] R. Poli, J. Kennedy, and T. Blackwell, "Particle Swarm Optimization: An Overview," *Swarm Intell*, vol. 1, pp. 33-57, 2007.

[4] W. H. Kersting, "Radial distribution test feeders," in *Power Engineering Society Winter Meeting, 2001. IEEE*, 2001, pp. 908-912 vol. 2.

CHAPTER 6

SUMMARY & FUTURE WORK

6.1 Contributions

Technological advancements in power system optimization, a progressive national energy policy and economic considerations will continue to be key factors in the spreading and implementation of distributed generation on the power system. Optimal DG sizing and placement on a distribution power system will play a critical role in providing valuable information concerning the impact of DG on a distribution power system.

Analysis techniques and indices were developed in MATLAB and interfaced with a well established distribution analysis software package. This research provides the user access to a flexible software tool with multiple analytical features that provides optimal solutions. This research also modified the rule of thumb calculation traditionally used in capacitor bank sizing and placement and presented a more suitable calculation for a multi-objective function for DG sizing and placement. The modified rule of thumb calculation was used to improve the simulation time and to minimize the probability of obtaining a local optimal solution in a larger search space.

In an effort to provide the power system engineer with a flexible and effective tool that adequately evaluates the impact of DG on a distribution power system, this dissertation proposed a multi-objective optimization index using the particle swarm algorithm to solve the optimal sizing and placement of multiple DGs for a distribution system. The primary contribution of this research is the development and application of multiple indices to evaluate the impact of DG on the following system parameters: voltages, system losses, fault currents and system reliability. These indices are computational efficient and provide an accurate assessment of the impact of DG. The algorithm is also capable of handling multiple DGs on a distribution system with n^{th} number of nodes. The algorithm will solve with a high rate of convergence and provide a near global optimal DG sizing and placement solution for the IEEE 13-Node, 34-Node and 123-Node Test Cases.

6.2 Future Work

To enhance the research, the optimal DG sizing and placement program can be embedded into the DSS program to improve the speed and overall performance of the algorithm. The MATLAB algorithm code can be written in the Delphi programming language and fully integrated into the distribution software package. Dynamic switching for system reconfiguration can be implemented to help improve the significance of the Reliability and Fault Current Indices.

Also, additional indices can be developed to take other parameters into consideration to assess the impact of DG on the distribution system. For example, harmonic analysis and a cost function can be utilized as factors in determining the optimal size and placement of DG. The DG sizing and placement problem can be analyzed under load varying and transient conditions to assess the impact of DG on system operations. The system can also be analyzed under various fault conditions to study the system response. The research can be expanded to consider other types of generators, and analyze the impact of various generator parameters on the performance of the DG and the consequential impact on the distribution system (i.e. power factor). The impact of the pre-screening method on the accuracy and speed of the algorithm can be explored under various system conditions.

The methods and techniques could also be compared to other evolutionary techniques to evaluate the performance. In the research, the rounding method was used to make the particle swarm discrete when solving for the optimal location. In order to improve the simulation speed, a better method can be developed to convert continuous variable to discrete variables to solve for the optimal location.